Interreg
North-West Europe
DGE-ROLLOUT

WP T2 Deliverable D2.2 Economic and environmental assessment of deep geothermal energy projects

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Disclaimer

This report was written as a research result for the DGE Rollout project. The cases were built in a techno-economic assessment tool which required adjustments of reality to the method, and presented results are produced with this simulation method. No guarantee or rights can be given based on the data and results presented in this report regarding accuracy, reliability, correctness or completeness of the information and materials, and no legal responsibility is accepted, for example regarding the risk or profitability of actual projects.

Geological and economic input data was gathered through experts, all with sufficient expertise in their research field and geographical area. Names and affiliations of some contributors are kept confidential, but all are explicitly thanked for providing their input.

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Introduction

The application of deep geothermal energy (DGE), as with any other industrial project, needs a business case for investors to support the project. Contrary to many other types of investments, DGE is very location-specific due to geology, and is therefore also inherently charged with large uncertainties and high up-front costs, increasing investment risk. In order to understand the influence of performance, cost and policy, a techno-economic assessment (TEA) is carried out.

This is formulated in the DGE Rollout project description as follows:

> ***"WP T2, Activity 2: Economic and environmental evaluation support schemes***
>
> *The techno-economic model for DGE, developed in the ALPI project, will be applied to a case for each region to evaluate the economics & environmental impact. Investment risk & risk reduction by exploration are essential in increasing DGE project success rates. The results from WP T1&3 will provide the context, policy scenarios & framework for interpretation. Results will show the economic thresholds, effectiveness of policy instruments & investor types, the environmental benefits as CO_2 reduction."*

An existing TEA method, based on expert input, will be adjusted and applied to four cases, one for each consortium country, and will be completed with an analysis of greenhouse gas emissions.

Methods

Techno-economic assessment

A techno-economic assessment (TEA) can be applied to assist in investment decision making by analysing its profitability. It involves building a cash flow model based on economic and technical performance. This TEA basis can be expanded with a sensitivity analysis for certain stochastic parameters. This, however, does not include managerial flexibility in making project decisions, that are necessary to counterbalance the uncertainties. In other words, a TEA without decision options only considers a now-or-never decision. The development of DGE projects relies heavily on knowledge gain through investment, and flexibility in any analysis is needed to make realistic assessments.

Compernolle et al. (2019) developed a TEA method for DGE including optionality, geological and economic uncertainty, based on a model for CO_2 geological storage by Welkenhuysen et al. (2013). In short, a project is assessed in two stages (figure 1). In the exploration phase, information on the subsurface is gathered through investment to reduce uncertainty, and a forecast is made on the operational phase of the project. This stage-gate approach is a simplified application of Real Options Analysis (Dixit & Pindyck, 1994). In the operational phase, the uncertain parameter values are updated to mimic uncertainty reduction. In the model by Compernolle et al. (2019), the first phase includes all investments until (and including) the first drilling of a DGE doublet. At this point, a decision is made to either stop the project or continue development in one of three options: a low-temperature heating application, low- and high-temperature heating, and low- and high-temperature heating combined with electricity production. In the TEA model, reservoir input data consists of three parameters: flow, temperature and depth, where the two former define the project's performance, and the latter the cost of drilling.

The full calculation comprising both phases is repeated in a Monte Carlo calculation, each time changing the value of the stochastic input parameters (geological resource and energy market prices). This results in a probabilistic distribution on project profitability, probability of success and influence of policy instruments.

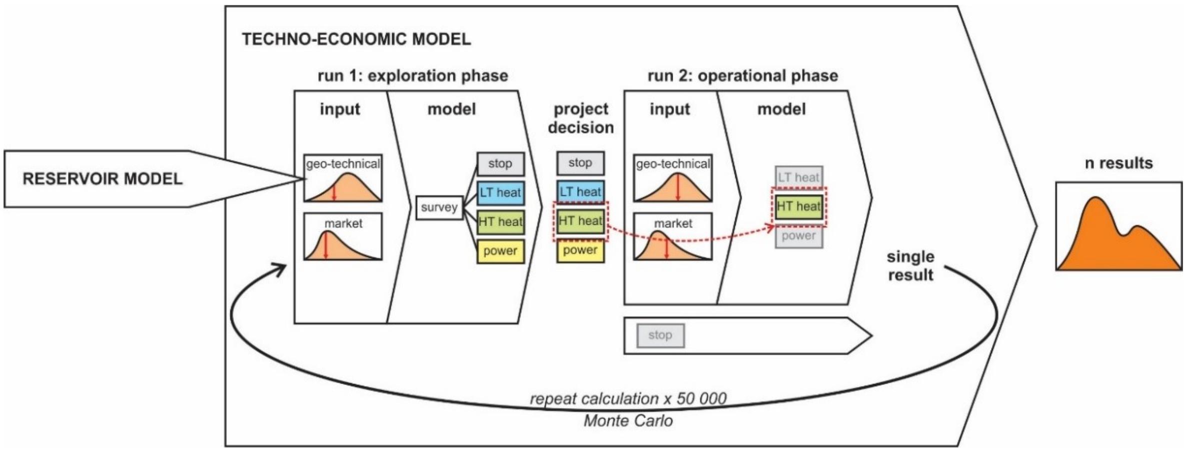


Figure 1. Flow scheme of the Monte Carlo-based TEA model, consisting of two steps separated by a decision moment.

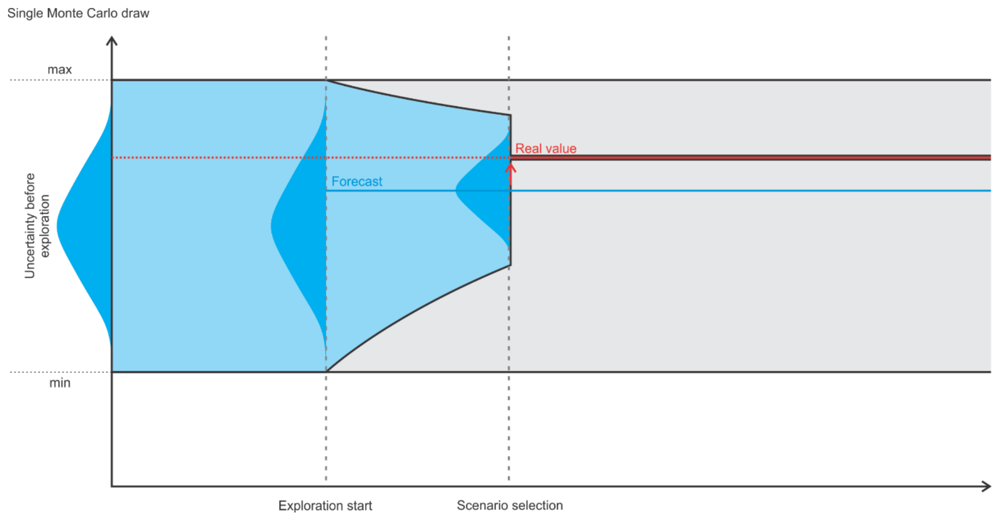


Figure 2. Representation of the evolution of technical (geological) uncertainty in the TEA model. In a single Monte Carlo draw, the forecast value (blue line) is drawn from the full uncertainty distribution. Forecasts are made based on this incomplete information. With time and investment, uncertainty is reduced. The real value is obtained as a second draw from this reduced uncertainty distribution.

The exploration phase of the TEA cash flow model has a duration of 5 years and the operational phase 35 years. Six parameters are treated as stochastic over the Monte Carlo calculation: the low-temperature heat market price, the high-temperature market price, the electricity market price (if applicable), well depth, flow and temperature. Figure 2 shows how the uncertainty of the last three (technical) parameters is modelled, with limited foresight (Welkenhuysen & Piessens, 2017).

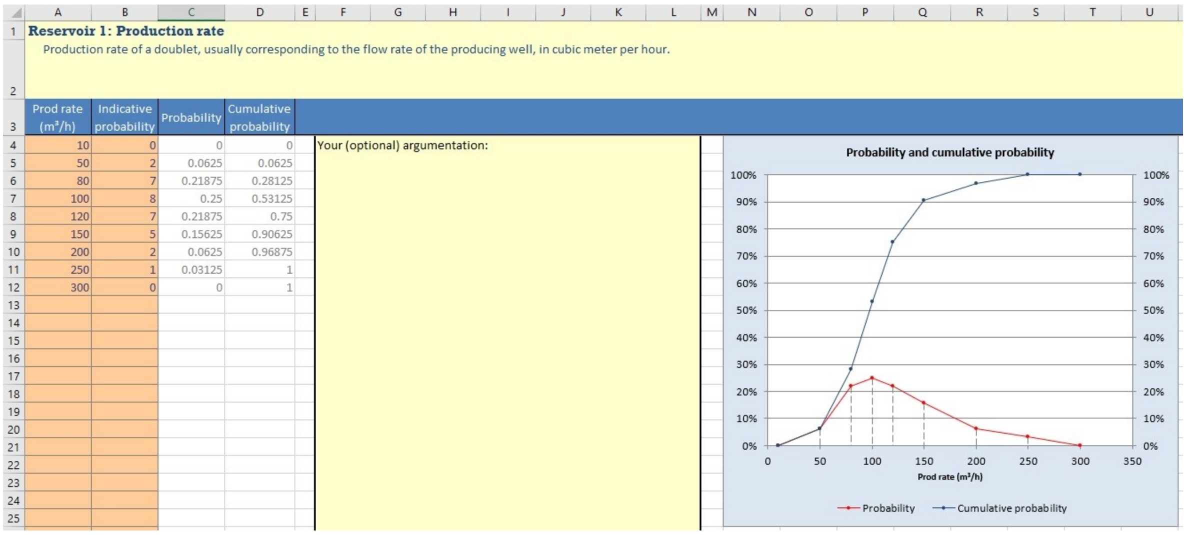
Except for heavily explored areas and active projects, (potential) subsurface targets for DGE inherently have large uncertainties that are relevant for their performance as a DGE project. For a realistic approach to reservoir data, a method was developed to gather this data through expert input, which enables the inclusion of the full uncertainty range and true current state of knowledge (Welkenhuysen et al., 2013). Figure 3 shows an example of parameter input in the expert inquiry document. Expert input was gathered as stochastic distributions on the following parameters:

- Geotechnical probability on reservoir failure (single value)
- Top depth of production
- Total thickness
- Productive thickness
- Geothermal gradient
- Fluid transmissivity
- Flow rate
- Effective porosity
- Optimal distance between the wells
- Optimal distance between doublets

Further on, the model uses the following technical boundary conditions:

- Maximum drawdown
- Production lifetime before breakthrough, in relation to the distance between wells
- Wellbore diameter

An analytical reservoir model, developed by Gringarten (1978; figure 4) for a geothermal doublet, is used with the input mentioned above, to calculate flow, temperature and depth. The redundancy between the input and result parameters allows for checking any input inconsistencies and highlights model limitations. This model is also run in a Monte Carlo calculation to combine the different parameters over the full uncertainty range. For the reservoir model, 100 000 calculations were run. For the TEA model, 10 000 iterations were run, which draw from the 100 000 reservoir model results. This number is sufficient for the results to have a precision of 1%. The full TEA model from Compernolle et al. (2019) has received an update for minor error corrections, and to accommodate for specific policy support schemes. Some data on policy support schemes was taken from Tasdemir & Arndt (2020).



Reservoir 1: Production rate

Production rate of a doublet, usually corresponding to the flow rate of the producing well, in cubic meter per hour.

Prod rate (m^3/h)	Indicative probability	Probability	Cumulative probability
10	0	0	0
50	2	0.0625	0.0625
80	7	0.21875	0.28125
100	8	0.25	0.53125
120	7	0.21875	0.75
150	5	0.15625	0.90625
200	2	0.0625	0.96875
250	1	0.03125	1
300	0	0	1

Figure 3. Expert input sheet for stochastic parameters.

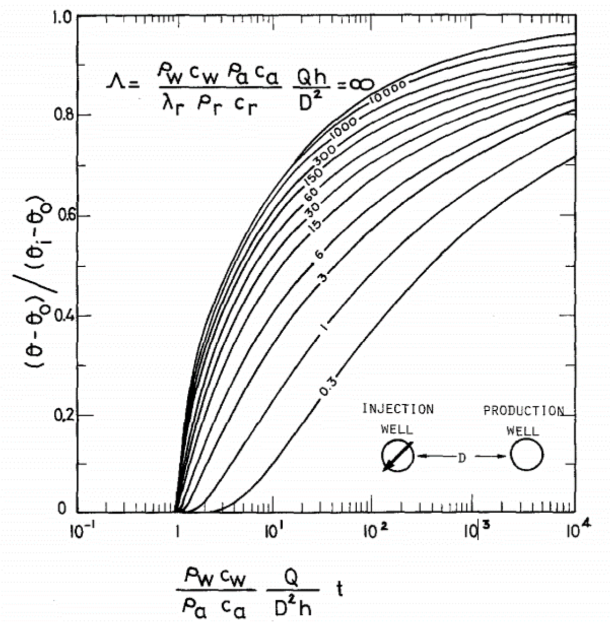


Figure 4. Relations in the Gringarten (1978) analytical model for geothermal heat extraction of a doublet, showing time versus production well temperature variation for various heat exchange coefficients.

Environmental assessment

An environmental assessment is made as a spreadsheet calculation of the greenhouse gas emission intensity. The main greenhouse gas emissions from a deep geothermal doublet occur from the energy needed for pumping, and from CH_4 (methane) by-catch from production. The coëfficient of performance (COP) factor determines the ratio of energy produced over energy consumed. When integrated into a heat network, additional emission sources occur: heat loss and a backup system (natural gas is chosen here). The introduction of a backup system also lowers the CH_4 by-catch emissions. Data on production and network emissions is mainly taken from Dijkstra et al. (2020), the deeper Permian case, reference year 2020. COP factors differ in literature. An average COP factor of 20 was chosen based on Dijkstra et al. (2020) and VITO Team geo et al. (2012). The energy used for pumping is assumed to be grid electricity, with an average grid greenhouse gas emission intensity per country, retrieved from EEA (2021). The emission intensity in Germany and the Netherlands is relatively high, due to a high share of fossil-based energy. For France, the emission intensity is much lower due to a higher share of nuclear energy. Belgium lies somewhat in between. For comparison, an individual natural gas central heating system is assumed, with emission data from Dijkstra et al. (2020). All input data is shown in table 1.

Parameter	Value	Unit	Source
Reference year	2020	year	Dijkstra et al. (2020)
COP	20	kWh/kWh	Dijkstra et al. (2020), VITO Team geo et al. (2012)
Natural gas central heating	0.2286	kgCO2e/kWh	Dijkstra et al. (2020)
CH4 by-catch production only	0.00792	kgCO2e/kWh	Dijkstra et al. (2020)
CH4 by-catch heat network	0.00612	kgCO2e/kWh	Dijkstra et al. (2020)
Heat network heat loss	0.02232	kgCO2e/kWh	Dijkstra et al. (2020)
Natural gas backup	0.04572	kgCO2e/kWh	Dijkstra et al. (2020)
Electricity production emission intensity Belgium	0.161	kgCO2e/kWh	EEA, 2021
Electricity production emission intensity Netherlands	0.3284	kgCO2e/kWh	EEA, 2021
Electricity production emission intensity Germany	0.311	kgCO2e/kWh	EEA, 2021
Electricity production emission intensity France	0.0511	kgCO2e/kWh	EEA, 2021

Table 1. Environmental assessment data for geothermal projects, heat networks and a natural gas alternative.

With this data, emission factors are calculated per country for a number of scenarios: with or without CH_4 by-catch (because CH_4 production varies depending on the geological setting), and as production only, or as a heat network. The avoided emission factor is calculated as the difference between the geothermal and natural gas system. Because the natural gas system shows emissions until/at the end user, the comparison and avoided numbers are most accurate for the heat network scenario.

Case selection

Four cases were selected among the project partners and countries to perform the techno-economic and environmental assessment:

- The Balmatt project in Mol, Belgium, developed by VITO.
- Two locations in the Netherlands, near Leeuwarden and near Nigtevecht.
- A theoretical case in the Hauts-de-France region, in the North of France.
- The Weisweiler project, Germany, under development by RWE, near the lignite powerplant.

Case Belgium

Case description

For Belgium, the Balmatt project developed by VITO in Mol, was chosen as a basis for the TEA. This project has coordinates latitude 51°13’27.98” N and longitude 5°06’32.38” E. This is an active project with a research focus. For the current case study, it was assumed that it was developed as a commercial project.

The Balmatt project drilled the Lower Carboniferous lime- and dolostones of the Carboniferous Limestone Group of the Campine Basin. The upper part of the sequence is formed by stacked shallow marine and reefal limestones that were deposited on a platform. The sequence is several hundreds of meters thick and can be subdivided into at least 3 major depositional cycles that are separated from each other by emersion horizons and/or erosional surfaces. The limestones rest conformably on a sequence of aggradating dolostones. The limestones and dolostones were deposited during the Early Carboniferous, some 320 million years ago. Since then, these rocks were subjected to a number of processes that have strongly influenced their porosity and permeability. This has resulted in a generally compact rock, locally cross-cut by highly permeable veins and fault zones. The Carboniferous Limestone Group was explored intensely in the western part of the Antwerp Campine. Initially, the aim was to find pockets of natural gas, but later on, exploration was continued in the framework of subsurface gas storage. In the end, this led to the development of the subsurface gas storage site of Loenhout.

The geotechnical constraints that were selected for this resource are:

- Maximum drawdown of 100 m
- Lifetime until breakthrough: 35 y
- Well radius: 0.0635 m

Scenario

For the Belgian case, two scenarios were developed, which represent different decision moments in time for the project. The first and earliest scenario “Before” assumes a situation before drilling, with corresponding larger uncertainties on the geotechnical parameters. For this, geological expert input was used from the ALPI project (Compernolle et al., 2019) which was gathered in 2016, when only the first well was completed. The second scenario “After” assumes the current level of knowledge (2021), as if a new doublet would be drilled with the current knowledge of the Balmatt project (with three wells drilled and production tested). In practice, this results in an updated and reduced uncertainty range for the geotechnical parameters.

For both scenarios, the decision moment lies between the first and second drilling, simulating knowledge gain through exploration, drilling and a pumping test to decide on the future development. Four development options are possible:

- Project abandonment.
- A low-temperature application (LT).
- A low- and high-temperature application (LT+HT).
- An LT+HT and electricity production application (LT+HT+EL).

The LT, HT and EL development options operate in a cascading system. The lower temperature limit for the LT option is 45°C, for the HT option 80°C, and for the EL option 110°C.

Two policy measures that apply to deep geothermal energy are added to the model:

- A feed-in tariff of 88€/MWh for renewable electricity production.
- A drilling insurance for deep geothermal projects ("waarborgregeling voor aardwarmteprojecten" in the Flemish region).

The latter system is quite complicated, and is added in the model as follows to insure the first drilling:

- An insurance premium of 7% is paid.
- If, after the first drilling, the option to stop the project is chosen, 85% of the insured amount is reimbursed if the realised part of the expected power (P90) is below 75%. If higher, there is no reimbursement.
- If, after the first drilling, the option to continue the project is chosen and the realised part of the expected power (P90) is below 100%, the reimbursed amount equals 85% multiplied by the non-realised part of the expected power multiplied by the insured amount. If the realised part is higher, there is no reimbursement.

Table 2 shows the environmental data. CO_2 emissions and emissions avoided in the results section are calculated using the CH_4 by-catch and heat network scenario.

	CH4 by-catch		No by-catch	
	Heat network	Production only	Heat network	Production only
Geothermal CO2 intensity (kgCO2e/kWh)	0.08221	0.01597	0.07609	0.00805
Natural gas central heating CO2 intensity (kgCO2e/kWh)	0.22860	0.22860	0.22860	0.22860
CO2 avoided (kgCO2e/kWh)	0.14639	0.21263	0.15251	0.22055

Table 2. Greenhouse gas emission factors for the Belgian case.

Simulation results

Scenario "Before"

In the scenario "Before", the average project value amounts to nearly 5 M€, with nearly 50% probability on a positive NPV (table 3). There is a 71% probability of a decision for an LT+HT project development, and a 29% probability of project abandonment. Only LT development is nearly never chosen, and the combined heat and power option is never chosen. Because of the latter, there is also no subsidy on the electricity produced. On the other hand, the insurance system is used in some cases. On average, about 200 k€ of public support is given. While this seems low to reimburse drilling costs, this includes the probability that the reimbursement is made, which occurs only in about 4% of the iterations. Comparing this public support to the project value, the gain ratio is 24: for every euro of public support spent, there is 24 € of private project value.

In the NPV histogram (figure 5) the Monte Carlo iterations are split up in the "abandon" and "operation" (all other) decisions. In case of abandonment, there is a clear peak around -10 M€. In case of continuation into operation, the mode is still negative, but there is a heavy tail on the positive side, reaching over 110 M€, though at a very low probability.

These results also show the benefit of the phase-gate approach. In a classical TEA, the 29% projects that were abandoned because of negative outlooks would have had a full operational phase. These have a higher probability of a negative NPV, significantly impacting the overall project value.

The average emissions in this scenario amount to nearly 7.9 ktCO_2e, which corresponds to 14 ktCO_2e avoided compared to decentral natural gas heating. These numbers are the averages for the projects that were chosen to be activated, and should be mentioned together with the development probability, about 70%. I.e. for 70% of the cases, there are on average 7.9 ktCO_2e of emissions; in 30% of the cases, there are no emissions from geothermal, but also no avoided emissions.

	Abandon	LT	LT+HT	LT+HT+EL
NPV	€ -7 960 696.95	€ -10 243 567.73	€ 10 283 339.78	€ -
Public contribution	€ 699 977.25	€ -	€ -	€ -
Probability total	29.13%	0.05%	70.82%	0.00%
Probability NPV<0	29.13%	0.05%	22.19%	0.00%
Probability NPV>0	0.00%	0.00%	48.64%	0.00%
Subsidy	€ -	€ -	€ -	€ -
Insurance	€ 699 977.25	€ -	€ -	€ -
Total average NPV	€ 4 959 120.85			
Total average public contribution	€ 203 882.99			
Total average societal value	€ 4 755 237.86			
Public support gain ratio	24.32			
Total average private investment	€ 14 835 089.36			
Total average public investment	€ 203 882.99			
Total average subsidy	€ -			
Total average insurance	€ 203 882.99			
Average emissions geothermal	7894.22	*tCO2e*		
Average emissions avoided	14057.11	*tCO2e*		

Table 3. TEA and emission results for the Belgian case, scenario “Before“.

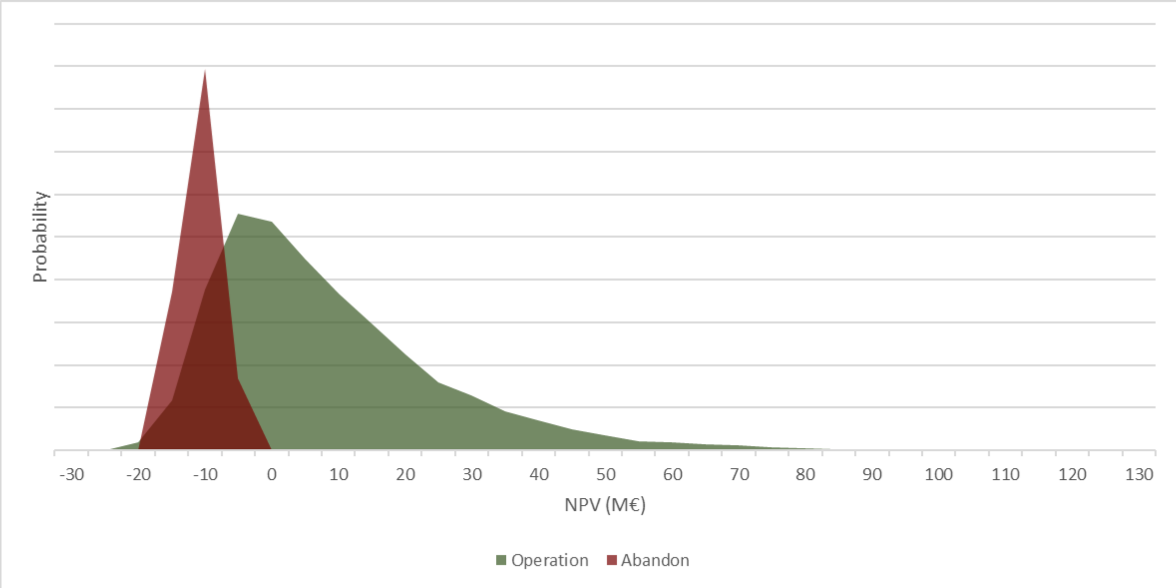


Figure 5. NPV histogram for the TEA results of the Belgian case, scenario “Before“. Bin width = 5M€.

Scenario “After”

In the scenario “After“, the results look quite different (table 4). The overall project value is higher, at 7.8 M€, and the probability that the project will be developed after the first drilling is increased to 96%. The probability of a negative NPV remains stable at 21%, but the probability of a positive NPV increased from 49% to 75%. This leaves a 4% probability that the project is abandoned after the first drilling, significantly lower than the 30% in the “Before” scenario. Because of the more positive values, the level of necessary public support is also lower at 148 k€ on average, as drill insurance remibursement, mostly after first drilling abandonment. This results in a public support gain ratio of over 50. In the NPV histogram (figure 6) the “peak” of abandoned projects is greatly reduced, and the range of the operational projects is squeezed into a smaller interval, without the long tail (up to about 60 M€ in this scenario). The mode has shifted towards the positive side, though. All this results in a more positive average project value and higher development probability.

The average emissions in the “After” scenario are very similar, indicating that the total energy output is expected to be similar. The total average emissions are 7.6 ktCO_2e, which corresponds to 13.5 ktCO_2e avoided compared to decentral natural gas heating.

Comparing the results of the “Before” and “After” scenarios shows that there is a significant value in the knowledge increase that took place in between, including the reduction of the NPV range as a decrease of uncertainty. As a simplified calculation, the value of the knowledge increase or exploration can be calculated as the difference between the NPVs, being 2.9 M€ in project value.

	Abandon	LT	LT+HT	LT+HT+EL
NPV	€ -5 810 899.35	€ -	€ 8 402 118.74	€ -
Public contribution	€ 3 313 840.30	€ -	€ 11 812.68	€ -
Probability total	4.14%	0.00%	95.86%	0.00%
Probability NPV<0	4.14%	0.00%	20.89%	0.00%
Probability NPV>0	0.00%	0.00%	74.97%	0.00%
Subsidy	€ -	€ -	€ -	€ -
Insurance	€ 3 313 840.30	€ -	€ 11 812.68	€ -
Total average NPV	€ 7 810 098.49			
Total average public contribution	€ 148 502.96			
Total average societal value	€ 7 661 595.53			
Public support gain ratio	52.59			
Total average private investment	€ 17 669 115.47			
Total average public investment	€ 148 502.96			
Total average subsidy	€ -			
Total average insurance	€ 148 502.96			
Average emissions geothermal	7607.31	*tCO2e*		
Average emissions avoided	13546.22	*tCO2e*		

Table 4. TEA and emission results for the Belgian case, scenario “After“.

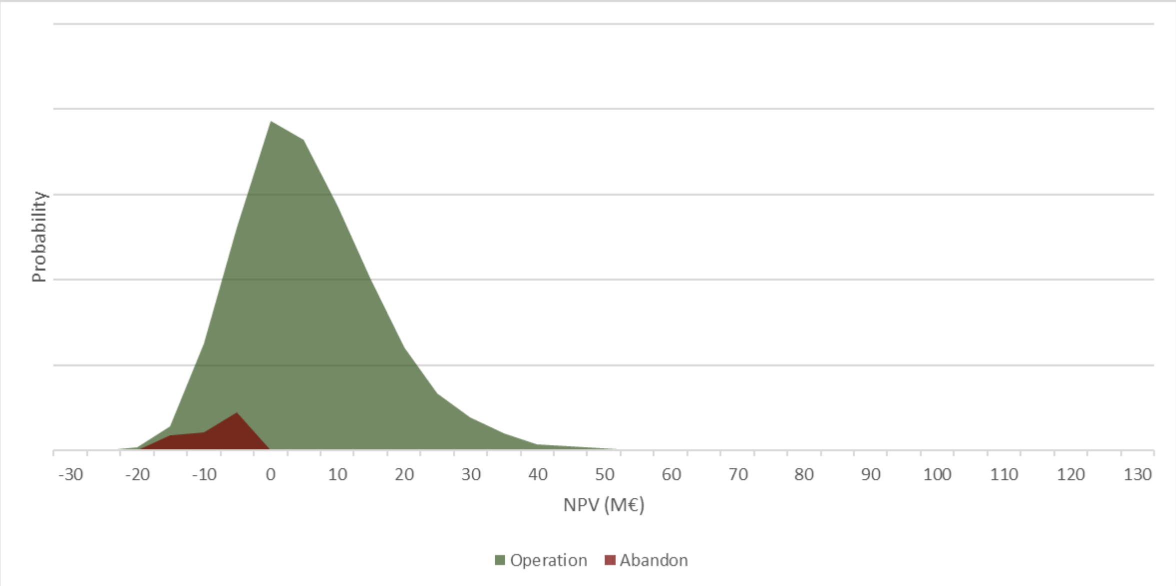


Figure 6. NPV histogram for the TEA results of the Belgian case, scenario “After“. Bin width = 5M€.

Case Netherlands

Case description

The Slochteren sandstone is very well known in the north of the Netherlands due to extensive gas exploration and production. In the central part of the Netherlands, where no hydrocarbons have been found, the information on this reservoir is more sparse. The sandstones have been deposited in an arid environment by eolian and fluvial processes. The interval varies in thickness due to infill of the paleorelief existing after the Hercynian tectonic phase. At the basin edge, the sandstones mainly have a fluvial facies and are several tens of meters thick. To the north, in the eolian facies, the thickness of the interval increases to 250 m. The sandstones have been deposited during the Late Permian around 260 million years ago and rest unconformably on deformed and eroded Carboniferous layers. Since the deposition, the reservoir has been subjected to different geological processes that have changed the initial reservoir properties. Compaction and diagenesis decreased the pore space and permeability of the reservoir. Tectonic inversion has brought more compacted rocks closer to the surface in some basins. Locally exposure of the Rotliegend during geological time has resulted in leaching of the rock and an improved secondary porosity and permeability.

Two locations of (potential) projects were selected:

- In Leeuwarden, at the location of the LEW-05 well. Subsurface information at this location is well known (so-called green spot), and is partly covered by 2D/3D seismic data. The location has coordinates latitude 53°10’18.61“ N and longitude 5°47‘0.61“ E.
- Near Nigtevecht, in between wells WRV-01 and WSP-01, which both had a very thin Rotliegend, assumed due to fault cut-out. Subsurface information is less well known (so-called white spot). It lies on a SCAN line, which still has to be processed. The location has coordinates latitude 52°16’33.31“ N and longitude 5°0‘48.85“ E.

The geotechnical constraints that were selected for this resource, for both locations are:

- Maximum drawdown of 450 m
- Lifetime until breakthrough: 30 y
- Well radius: 0.159 m

Table 5 shows the environmental data. CO_2 emissions and emissions avoided in the results section are calculated using the CH_4 by-catch and heat network scenario.

	CH4 by-catch		No by-catch	
	Heat network	**Production only**	**Heat network**	**Production only**
Geothermal CO2 intensity (kgCO2e/kWh)	0.09058	0.02434	0.08446	0.01642
Natural gas central heating CO2 intensity (kgCO2e/kWh)	0.22860	0.22860	0.22860	0.22860
CO2 avoided (kgCO2e/kWh)	0.13802	0.20426	0.14414	0.21218

Table 5. Greenhouse gas emission factors for the Dutch case.

Scenarios

Because for the Netherlands case two locations were chosen, only one scenario is developed. For this scenario also, the decision moment lies between the first and second drilling, simulating knowledge gain through exploration, drilling and a pumping test to decide on the future development. Three development options are possible:

- Project abandonment.
- A low-temperature application (LT).
- A low- and high-temperature application (LT+HT).

The LT and HT development options operate in a cascading system. The lower temperature limit for the LT option is 35°C, for the HT option 60°C.

Two policy measures that apply to deep geothermal energy are added to the model. A subsidy on renewable heat is simulated as a feed-in tariff of 40 €/MWh, with a cap of 24 €/MWh. This simulates the "Stimulering Duurzame Enrgieproductie" (SDE++). For example, if the heat market price is 10 €/MWh and production cost is 50 €/MWh, the theoretical subsidy level would be 30 €/MWh, which is capped at 24 €/MWh. Additionally, a cap on the total amount of subsidised energy amounts to the P50 value of the expected power output at 6000 running hours per year.

A drilling insurance for deep geothermal projects, very similar to the Belgian/Flemish system, is also modelled ("Risico's dekken voor Aardwarmte"). Also similarly, the actual insurance system is quite complicated, but for the current case was modelled as follows:

- An insurance premium of 7% is paid.
- If, after the first drilling, the option to stop the project is chosen, 85% of the insured amount is reimbursed if the realised part of the expected power (P90) is below 75%. If higher, there is no reimbursement.
- If, after the first drilling, the option to continue the project is chosen and the realised part of the expected power (P90) is below 100%, the reimbursed amount equals 85% multiplied by the non-realised part of the expected power multiplied by the insured amount. If the realised part is higher, there is no reimbursement.

Simulation results

Location Leeuwarden

At the Leeuwarde location, the well-known good subsurface properties result in a profitable result (table 6). In over 95% of the iterations, investments are made beyond the first doublet well. This results in a positive NPV with an 85% probability. The total average NPV is 23.7 M€. In case of abandonment, nearly always an insurance reimbursement is granted for the first well. In case the project continues to the operational phase, there are high subsidies of 23.5 M€ on average. Because of this, the average total societal value of the project is slightly negative. On the NPV historgam (figure 7) it is also clear that there is only a small probability of project abandonment. On the other hand, the operational projects show a large and nearly symmetrical bulge around about 20M€.

The average emissions amount to 11.5 ktCO_2e, which corresponds to 17.5 ktCO_2e avoided compared to decentral natural gas heating. Together with a very high development probability, this project seems to be a favourable climate mitigation investment.

	Abandon	LT	LT+HT
NPV	€ -6 826 154.42	€ -	€ 23 715 540.83
Public contribution	€ 1 968 273.83	€ -	€ 24 724 137.70
Probability total	4.74%	0.00%	95.26%
Probability NPV<0	4.74%	0.00%	10.41%
Probability NPV>0	0.00%	0.00%	84.85%
Subsidy	€ -	€ -	€ 24 713 007.60
Insurance	€ 1 968 273.83	€ -	€ 9 252.33
Total average NPV	€ 22 262 460.57		
Total average public contribution	€ 23 643 184.46		
Total average societal value	€ -1 380 723.89		
Public support gain ratio	0.94		
Total average private investment	€ 18 826 764.53		
Total average public investment	€ 102 552.63		
Total average subsidy	€ 23 541 184.74		
Total average insurance	€ 102 100.29		
Average emissions geothermal	11492.75	tCO2e	
Average emissions avoided	17511.92	tCO2e	

Table 6. TEA and emission results for the Dutch case, location Leeuwarden.

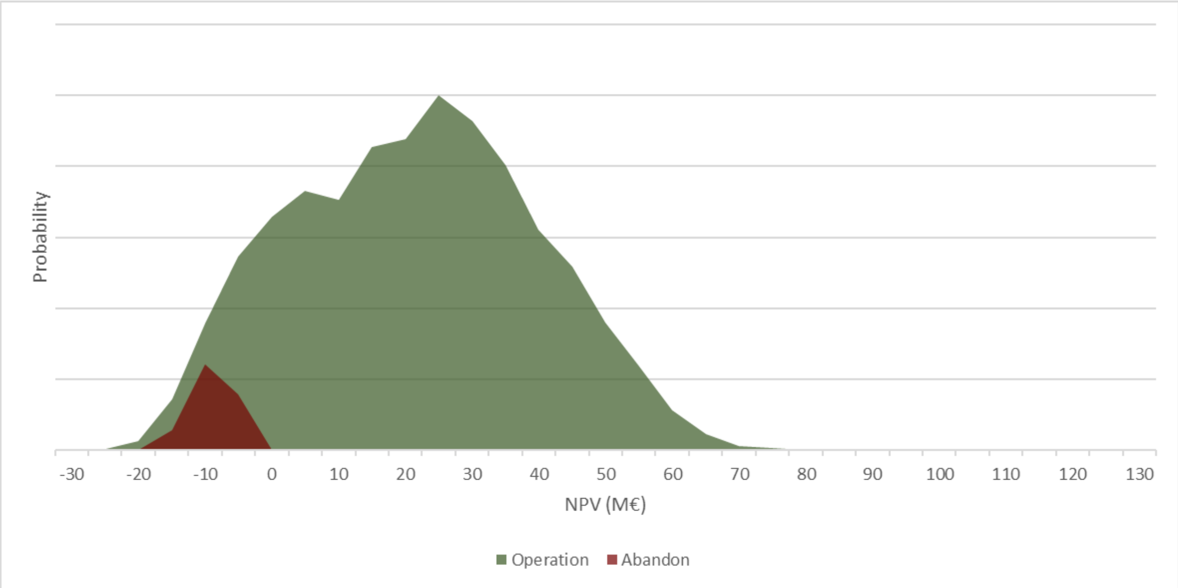


Figure 7. NPV histogram for the TEA results of the Netherlands case, location Leeuwarden. Bin width = 5M€.

Location Nigtevecht

Although the target strata for the Nigtevecht location are similar, the difference in location and knowledge level are big (table 7). Overall project value has dropped to 180 k€, with a project abandonment probability of 55% and a probability of a positive NPV of 34%. This shows the need for additional exploration at this location, for a more unambiguous and conclusive project value. The public support ratio of only 0.04 supports this conclusion, with 5 M€ of support to obtain a low average project value. The NPV histogram (figure 8) also shows these differences to the Leeuwarden location, with a high and narrow peak at around -10M€. Due to the low development probability of 45% and the very concentrated peak of abandoned projects, the probability curve of the operational projects is low.

Average greenhouse gas emissions for the Nigtevecht case amount to 13 ktCO_2e, slightly higher compared with the Leeuwarden case, due to a higher average energy output. The amount of avoided emissions is also higher at 20 ktCO_2e.

	Abandon	LT	LT+HT
NPV	€ -7 182 813.86	€ -	€ 9 232 637.13
Public contribution	€ 58 263.42	€ -	€ 11 129 640.32
Probability total	55.14%	0.00%	44.86%
Probability NPV<0	55.14%	0.00%	11.35%
Probability NPV>0	0.00%	0.00%	33.51%
Subsidy	€ -	€ -	€ 11 129 640.32
Insurance	€ 58 263.42	€ -	€ -
Total average NPV	€ 180 421.13		
Total average public contribution	€ 5 024 386.48		
Total average societal value	€ -4 843 965.35		
Public support gain ratio	0.04		
Total average private investment	€ 12 182 411.98		
Total average public investment	€ 32 129.06		
Total average subsidy	€ 4 992 257.42		
Total average insurance	€ 32 129.06		
Average emissions geothermal	13173.23	tCO2e	
Average emissions avoided	20072.52	tCO2e	

Table 7. TEA and emission results for the Dutch case, location Nigtevecht.

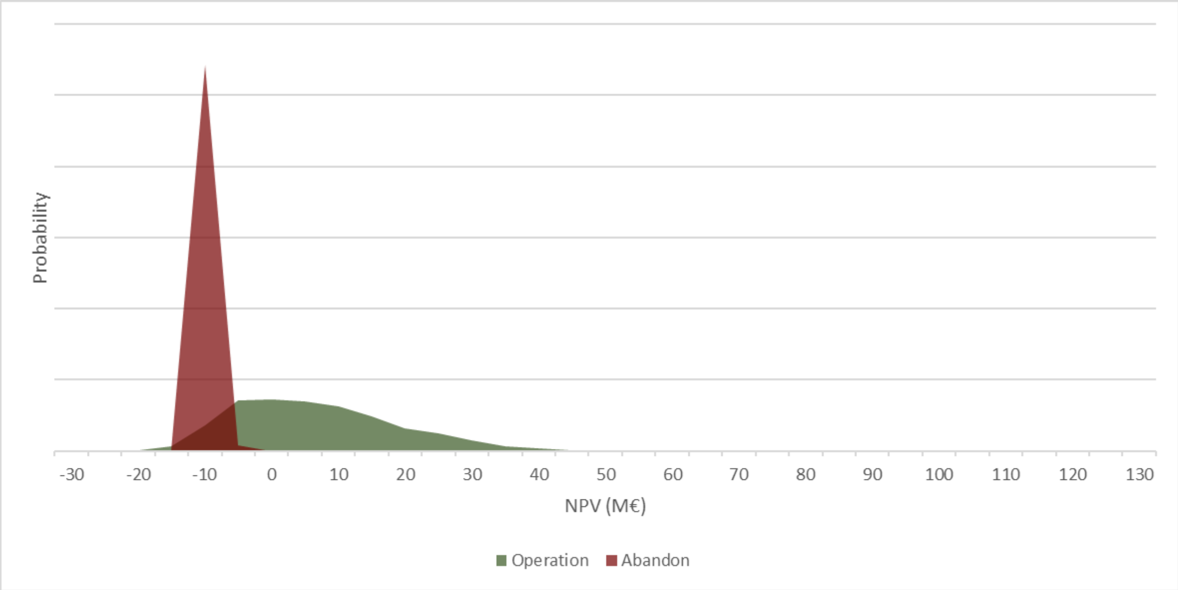


Figure 8. NPV histogram for the TEA results of the Netherlands case, location Nigtevecht. Bin width = 5M€.

Case France

Case description

The target resource in the Hauts-de-France region are the Lower Carboniferous lime- and dolostones of the Carboniferous Limestone Group in the area between Jeumont and Arras, and Saint Amand les Eaux and south of Cambrai. Its depth varies very strongly in northern France, and deepens southward with an overall monoclinal geometry, from 0 to 7000 m. The area is quite large, so no exact coordinates are given for this case. The expert input reflects the variability within the area of interest.

The geotechnical constraints that were selected for this resource are:

- Maximum drawdown of 100 m
- Lifetime until breakthrough: 35 y
- Well radius: 0.10795 m

Table 8 shows the environmental data. CO_2 emissions and emissions avoided in the results section are calculated using the CH_4 by-catch and heat network scenario.

	CH4 by-catch		No by-catch	
	Heat network	**Production only**	**Heat network**	**Production only**
Geothermal CO2 intensity (kgCO2e/kWh)	0.07672	0.01048	0.07060	0.00256
Natural gas central heating CO2 intensity (kgCO2e/kWh)	0.22860	0.22860	0.22860	0.22860
CO2 avoided (kgCO2e/kWh)	0.15189	0.21813	0.15801	0.22605

Table 8. Greenhouse gas emission factors for the French case.

Scenario

One scenario for this case is developed. The decision moment lies between the first and second drilling, simulating knowledge gain through exploration, drilling and a pumping test to decide on the future development. Three development options are possible:

- Project abandonment.
- A low-temperature application (LT).
- A low- and high-temperature application (LT+HT).

The LT and HT development options operate in a cascading system. The lower temperature limit for the LT option is 35°C, for the HT option 70°C.

Two policy measures that apply to deep geothermal energy are added to the model. A subsidy on renewable heat is simulated as a feed-in tariff which depends on the market price, with a cap of a maximum of 7 €/MWh. Thus, the difference between the production cost and the market price is covered by the feed-in tariff, up to 7 €/MWh. This simulates the Renewable heat fund (Fonds chaleur renouvelable) by ADEME in France.

A drilling insurance for deep geothermal projects is also modelled, simulating the short-term guarantee fund of the SAF Enfironment. For the current case it was modelled as follows:

- An insurance premium of 3.5% is paid
- If, after the first drilling, the option to stop the project is chosen, 90% of the insured amount is reimbursed if the realised part of the expected power (P90) is below 75%. If higher, there is no reimbursement.
- If, after the first drilling, the option to continue the project is chosen and the realised part of the expected power (P90) is below 100%, the reimbursed amount equals 90% multiplied by the non-realised part of the expected power multiplied by the insured amount. If the realised part is higher, there is no reimbursement.

Simulation results

The development probability of the Hauts-de-France case is evenly spread over the development options, with a 32% probability of project abandonment, 39% for the low-temperature application, and 29% for the low and high temperature application (table 9). In comparison to the previously discussed cases, this is the only one with a significant probability of an only-low-temperature application. This is mostly due to the large depth range that is supplied as input, including a significant amount of options where higher temperatures are not available. Because of the inclusion of the very deep options in combination with relatively high energy market prices (70 €/MWh), there is a significant chance of very high revenues and subsequent NPV's, with an average of 117 M€.

On the NPV histogram (figure 9) it can be observed that there is a very long tail, up to 1800 M€, with a very low probability, though these extreme values increase the average NPV significantly. These extreme values correspond to the extremes of input values, with large depths and high temperatures. For the HT+LT option, this even amounts to almost 200 M€ on average. Opposed to this are fairly high public support numbers, of 15 M€ on average. Still, the public support gain ratio is 7.7. Comparing the probabilities on positive and negative NPV, it shows that the Real Options system of a decision moment, in this case, is a very good discriminator. I.e. abandoned projects are mostly negative, operational projects positive.

The average emissions amount to 12.6 ktCO_2e, which corresponds to 25.0 ktCO_2e avoided compared to decentral natural gas heating. The ratio between both is sligtly higher for this case compared to the others because the electricity used in the geothermal projects is relatively carbon-lean due to a high share of nuclear power production.

	Abandon	LT	LT+HT
NPV	€ -3 599 555.75	€ 155 394 676.40	€ 198 053 805.01
Public contribution	€ 3 939 859.03	€ 18 939 620.80	€ 22 375 645.16
Probability total	32.02%	38.92%	29.07%
Probability NPV<0	32.02%	3.29%	0.74%
Probability NPV>0	0.00%	35.63%	28.33%
Subsidy	€ -	€ 10 615 981.18	€ 13 032 431.12
Insurance	€ 3 939 917.68	€ 8 323 639.62	€ 9 343 214.04
Total average NPV	€ 116 883 854.05		
Total average public contribution	€ 15 135 773.59		
Total average societal value	€ 101 748 080.47		
Public support gain ratio	7.72		
Total average private investment	€ 13 195 974.48		
Total average public investment	€ 7 216 406.92		
Total average subsidy	€ 7 919 475.65		
Total average insurance	€ 7 216 269.13		
Average emissions geothermal	12639.72	tCO_2e	
Average emissions avoided	25024.07	tCO_2e	

Table 9. TEA and emission results for the Hauts-de-France case.

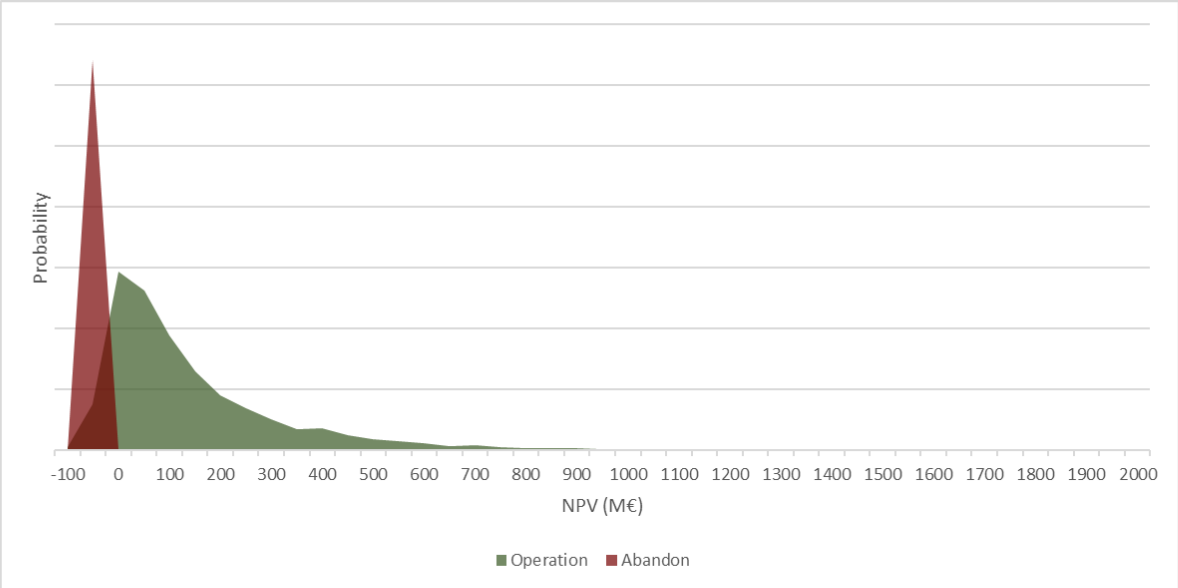


Figure 9. NPV histogram for the TEA results of the Hauts-de-France case. Bin width = 50 M€.

Case Germany

Case description

At the premises of the Weisweiler lignite power plant in Germany, owned by the energy company RWE, a deep geothermal project is under development. This project has coordinates latitude 50°50’06.51” N and longitude 6°18’39.28” E. Three scenarios define the target reservoir for a deep geothermal installation at the Weisweiler, geologically located in the Rhenohercynian Basin. Firstly, the Lower Carboniferous Kohlenkalk lime- / dolostones can provide heat at a relatively shallow depth. In a second scenario, the deeper Middle to Upper Devonian Massenkalk limestones are targeted. A third scenario includes the possibility that both Kohlenkalk and Massenkalk may also occur at greater depth levels below three thrust faults. These scenarios represent the current state of knowledge, which may be refined following an exploration drilling in early 2022 and later seismic campaigns. The input provided here integrates the assessments of all three scenarios.

The geotechnical constraints that were selected for this resource are:

- Maximum drawdown of 100 m
- Lifetime until breakthrough: 35 y
- Well radius: 0.0635 m

Table 10. shows the environmental data. CO_2 emissions and emissions avoided in the results section are calculated using the CH_4 by-catch and heat network scenario.

	CH4 by-catch		No by-catch	
	Heat network	**Production only**	**Heat network**	**Production only**
Geothermal CO2 intensity (kgCO2e/kWh)	0.08971	0.02347	0.08359	0.01555
Natural gas central heating CO2 intensity (kgCO2e/kWh)	0.22860	0.22860	0.22860	0.22860
CO2 avoided (kgCO2e/kWh)	0.13889	0.20513	0.14501	0.21305

Table 10. Greenhouse gas emission factors for the German case.

Scenario

One scenario for this case is developed. The case simulation is slightly different here compared to the other cases. While for the others, there is a decision moment in between both wells of a doublet configuration, for the Weisweiler case it was chosen to have the decision moment between the drilling of the exploration well and the drilling of both doublet wells.

Four development options are possible:

- Project abandonment.
- A low-temperature application (LT).
- A low- and high-temperature application (LT+HT).
- An LT+HT and electricity production application (LT+HT+EL).

The LT, HT and EL development options operate in a cascading system. The lower temperature limit for the LT option is 45°C, for the HT option 80°C, and for the EL option 110°C.

One policy measure that applies to deep geothermal energy is added in the model. A subsidy on renewable electricity is simulated as a feed-in tariff which depends on the market price, with a cap of amaximum of 252 €/MWh. This simulates the Renewable Energy Sources Act ("Erneuerbare-Energien-Wärmegesetz", EEG) in Germany. In reality this amount decreases throughout time, though it has now been fixed for several years (Tasdemir & Arndt, 2020). Because of the effect of discounting, a fixed amount was assessed to be sufficiently realistic. Subsidies on renewable heat produced were not found for Germany in Tasdemir & Arndt (2020). Several supprot schemes on investment are available, but this support scheme is not present in the model.

A drilling insurance for deep geothermal projects is available in Germany ("Fündigkeitsrisiko Tiefengeothermie"), but cannot be modeled with the current model setup. In the model, the insurance covers the first well, drilled before the decision moment. For the current case, however, only the exploration well precedes the decision moment. Exploration wells are not eligible for this insurance.

Simulation results

The Weisweiler case in Germany results in an operational project with a 48% probability, considering the scenario above (table 11). In most iterations, a low-temeprature+high-temperature project is developed (46%, of which 34% with a positive NPV). The total average NPV amounts to just under 3 M€. In case of LT+HT development, the average NPV rises to 11.7 M€. Electricity production is never chosen as an economic option, and because electricity subsidy is the only simulated public support measure, there is no public support in the results. In the histogram (figure 10) a significant peak in operational projects can be observed around the zero mark. However, due to the specific configuration of the target reservoir (three possible target layers, of which one at large depth but with low probability), there is a very long but low tail, stretching up to 600 M€, nearly invisible on the histogram. Without additional public support, this target should be reached in order to have a successful project. With additional support, the other targets could also provide viable projects.

The average emissions amount to 14.9 ktCO2e, which corresponds to 23.1 ktCO2e avoided compared to decentral natural gas heating. This is fairly high, comparable to the Hauts-de-France case, due to the high capacity.

	Abandon	LT	LT+HT	LT+HT+EL
NPV	€ -4 443 181.82	€ -5 970 444.88	€ 11 678 083.19	€ -
Public contribution	€ -	€ -	€ -	€ -
Probability total	52.35%	1.40%	46.25%	0.00%
Probability NPV<0	52.35%	1.33%	12.63%	0.00%
Probability NPV>0	0.00%	0.07%	33.62%	0.00%
Subsidy	€ -	€ -	€ -	€ -
Total average NPV	€ 2 993 999.78			
Total average public contribution	€ -			
Total average societal value	€ 2 993 999.78			
Public support gain ratio	-			
Total average private investment	€ 9 126 836.80			
Total average public investment	€ -			
Average emissions geothermal	14895.57	tCO2e		
Average emissions avoided	23061.48	tCO2e		

Table 11. TEA and emission results for the Weisweiler case in Germany.

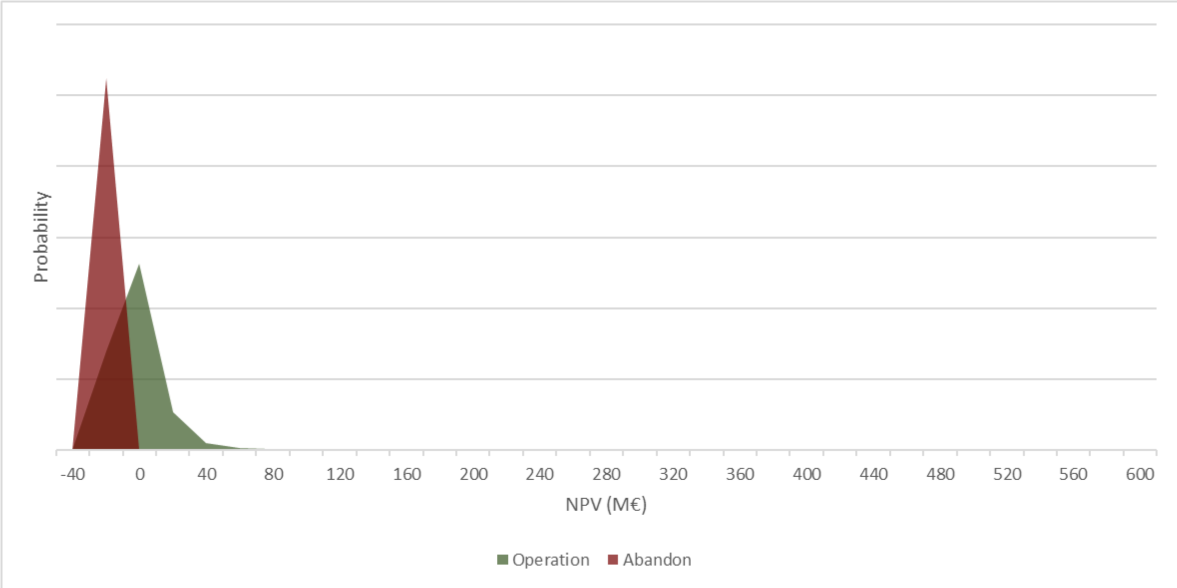


Figure 10. NPV histogram for the TEA results of the Weisweiler case. Bin width = 20 M€.

Conclusions and recommendations

Different cases and scenarios of deep geothermal energy applications are investigated in a techno-economic assessment applying a basic Real Options approach, through the inclusion of a decision moment. This method ensures a more realistic outcome compared to a classical linear TEA where all possible scenarios result in an operational project, even if not profitable. Though, because of the limited foresight, imperfect decisions can still be taken.

In general, NPV and development probability results show that profitable projects are possible, but public support remains necessary in many cases to lower the risk. For example for the Weisweiler case in Germany, only the outlooks of a very profitable but low probability scenario, if the deepest target is possible, produces the positive NPV result. Without these outlooks, or additional public support, the average NPV would be negative.

Similarly, the large range of depths and corresponding temperatures in the Hauts-de-France case results in some extreme values. Although not unrealistic and providing a good overview of available options, it would be recommended for future and more targeted assessments to investigate separate, more restricted areas/volumes.

On the other hand, projects that are already further in their development show lower investment risk, such as the Balmatt project, scenario “After” in Belgium, and the Leeuwarden case in the Netherlands. In particular, comparing the “Before” and “After” scenarios of the Balmatt case, and the Leeuwarden and Nigtevecht cases shows the value of additional subsurface exploration.

In all scenarios and for all cases, high-temperature heat production is chosen as the most promising development option. Of the cases where electricity production is an option, this was never chosen because of the relatively high cost and low temperatures.

Deep geothermal plants still produce a significant amount of greenhouse gasses, in particular CO_2. A basic environmental assessment was made for these emissions, including emissions from CH_4 by-catch. Avoided emissions, in comparison with decentral gas-fired heating systems, amount to between 13 and 25 ktCO_2e, depending on the case. These avoided emissions are roughly twice the amount of emissions from the geothermal project.

In future research, it is recommended that the TEA method is expanded to accommodate for public support through capital investment. Additionally, the amount of decision moments could be increased to provide an even more realistic approach to risk and flexibility. The environmental analysis can be improved by expanding towards a full life cycle analysis (LCA).

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