Towards geological-economic modelling to improve evaluating policy instruments for geothermal energy - Case study for Belgium (Campine Basin)

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Deep geothermal energy appears to be currently on the edge of a take-off in Belgium. However, the actual emergence of this technology is subject to developments in legislation and incentives from regional governments. Different risk/return expectations across stages of the investment continuum exist and the financial structures that are employed at each stage may require different types of public support. In this context, the ALPI project aims at developing a geological-economic model to calculate the impact of different policy instruments on development of the Belgian geothermal energy sector. Due to the lack of underground information describing the Campine Basin, economic methods are used to deal with these large geological uncertainties.

L'énergie d'origine géothermique profonde apparait actuellement, en Belgique, comme en passe de décoller. Cependant l'émergence actuelle de cette énergie est liée aux développements d'ordre législatif et incitatif de la part des gouvernements régionaux. Les attentes différentes en termes de risques/bénéfices tout au long des étapes d'un investissement en continu sont présentes et les structures financières, utilisées à chaque étape, pourraient exiger différentes sortes de support public. Dans ce contexte, le projet ALPI a pour objectif de développer un modèle géologique et économique pour le calcul de l'impact des différents outils politiques sur le développement du secteur énergétique de la géothermie en Belgique.

La energía geotérmica profunda parece estar cerca de despegar en Bélgica. Sin embargo, la emersión real de esta tecnología depende de la evolución de la legislación y de incentivos de los gobiernos regionales. Diferentes expectativas de riesgo / retorno existen a través de las distintas etapas de inversión, siendo necesario diferente tipo de apoyo público en cada una de dichas etapas. y las estructuras financieras que se emplean en cada etapa puedan necesitar diferentes tipos de apoyo público. En este contexto, el proyecto ALPI tiene como objetivo desarrollar un modelo geológico-económico para calcular el impacto de los diferentes instrumentos de la política para el desarrollo del sector geotérmico belga. Debido a la falta de información existente en la Cuenca de Campine, los métodos económicos se utilizan para hacer frente a estas grandes incertidumbres geológicas.

Belgium is one of the most densely populated countries in the world (363 inhabitants/km² in 2015) with a population density similar to that of Japan, India and the neighbouring Netherlands. The ambitious European 20-20-20 goals play an important role in incentivising the upward trend of Renewable Energy Sources (RES) and geothermal energy in Belgium. These targets require 13% of total energy consumption in Belgium to be produced from RES in 2020. In 2011 RES comprised 5.1 % of total energy consumption.

The past five to ten years have seen a substantial effort in geothermal research and development in Belgium (USD 14.42 million) between 2010 and 2015). Despite being in an intra-continental setting, it was demonstrated by several national, regional and cross-European projects that favourable geological conditions for geothermal energy may exist over large regions of Belgium, yet these conditions are mostly based on sparse exploratory data and indirect determination.

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A great deal of uncertainty remains due to the lack of deep exploration boreholes, leading to high geological risk. This geological uncertainty was highlighted in the 1980s with the failure of the Meer geothermal well in the Campine Basin, due to Namurian strata thickening significantly above the targeted Dinantian limestones, a fact previously unknown. This led to a bottleneck for geothermal projects during several decades. However, recent projects (Balmatt wells) will improve geological understanding.

In anticipation of the opening-up of the deep geothermal market in Belgium, Hasselt University, the University of Antwerp and the Geological Survey of Belgium are investigating the regional potential for geothermal heat and electricity production.

Petitclerc *et al.* (2016) developed a methodology to refine the probability of success for a geothermal investment. This methodology also forms the first step in integrating geological modelling in techno-economic simulations. This paper focuses on how to fully account for geological uncertainties in the overall economic evaluation, which allows the level of geological knowledge to be directly linked to the economic viability of potential future projects.

Geological setting

The Belgian subsurface presents a large geological diversity resulting from tectonic events and the evolution of different sedimentary basins over a period of 550 million years. The sedimentary basins in the northeast (Campine Basin) and south

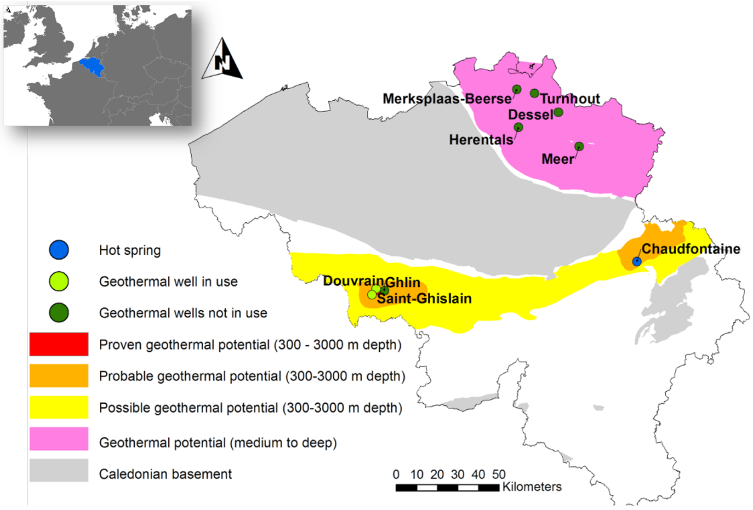


Figure 1: Mapped medium-deep geothermal potential and geothermal wells in Belgium. Inset shows location of Belgium in Europe (Loveless et al. *2015):*

(Namur-Dinant Basin) of Belgium (Dreesen *et al.*, 1985) provide the largest potential for deep geothermal energy. The recognised geothermal resources and hydrothermal processes observed in Belgium are localised in the thick sequences (up to 500 m) of Devonian-Carboniferous platform carbonates. However, the basins differ in structure and characteristics. This case study focuses on the Campine Basin, which is an intermediate basin between the Brabant Massif and the Roer Valley Graben (itself an extension of the active Lower Rhine Graben) primarily within the Netherlands. Much of the knowledge of the subsurface of Flanders comes from seismic surveys undertaken since the 1950s.

In the 1970s and '80s, five geothermal wells (Meer, Merksplas, Dessel, Turnhout and Herentals) were drilled in Flanders in the low temperature chalk and Dinantian reservoirs, but none of these wells remains in operation today (***Figure 1***). Deep geothermal targets have been mapped for some exploration (Vandenberghe, 1990) and exploitation projects. The most recent project in Flanders, (the Geoheat-App project in 2014) better defined the geothermal potential of four reservoir intervals across the border with the Netherlands.

Methodology

Use of decision tree

The probability of success of a deep geothermal project is typically rather low, especially when the level of knowledge of the reservoir is still at a regional level. This may lead to a situation where there is a general consensus that a reservoir is well suited for geothermal development, but its actual development is hampered by the high geological, technical and financial risks of individual projects.

Zooming in on this hurdle requires a methodology which deals with virtual project simulations to evaluate what types of projects could work and which kind of policy instruments could be implemented. A decision tree was set up (***Figure 2***) to reflect the pre-investment point of view of a private investor. This investor analyses one single case study to be executed in a defined region, and has to optimise the outcome in terms of return on invested capital. Policy instruments are considered as external factors that change the investment conditions.

During the elaboration of such a project, the project team goes through several decision stages, each based on the information gained from the previous stage, with an evolution of the risk that the project fails (is abandoned). The liberty that the investor has to redirect or abandon the project at each step is incorporated as detailed in Petitclerc *et al.* (2016).

Outcomes of a geothermal decision tree

The decision tree model (***Figure 2***) reflects the generic development of a deep geothermal project, applied to the Campine Basin in Belgium, and is similar to that of the deep geothermal project that is currently under development (the Balmatt project).

Depending on the water temperature and the flow rate, several options are available in the pre-project simulation: Failed; Low-Temperature (LT) heat plant; High-Temperature (HT) heat plant; and a Binary power plant with or without Enhanced Geothermal System (EGS). Due to the medium temperature gradient (25 °C to 30 °C/km) in Belgium, only the binary power plant is relevant for electricity production.

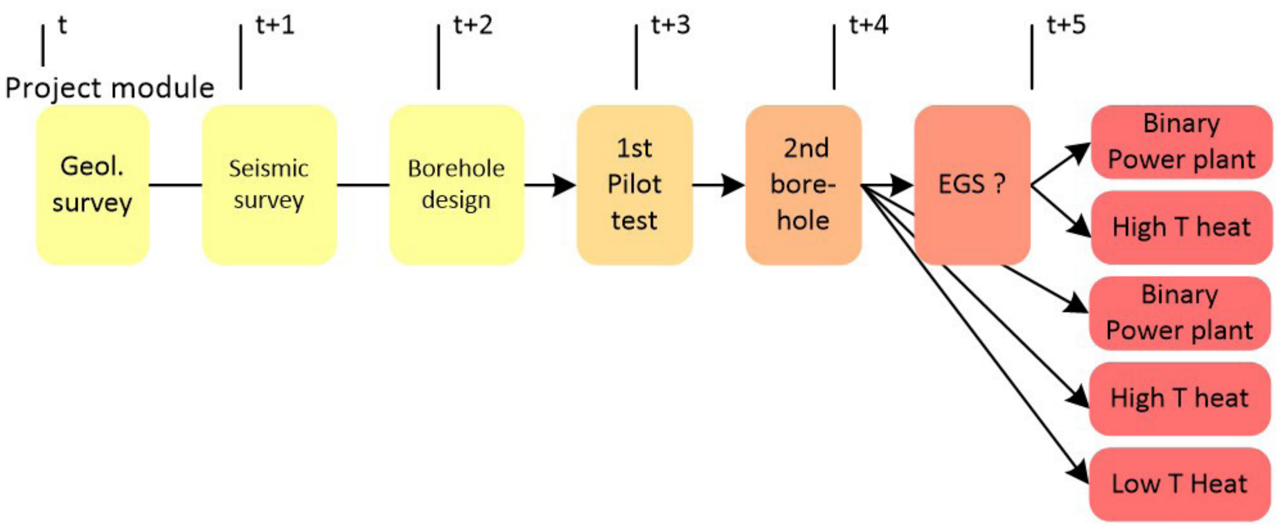


Figure 2: Decision model for the generic Campine Basin deep geothermal project (based on the Balmatt site).

A significant upfront investment is related to the drilling, posing an important risk for a geothermal project. In reaction to this, risk insurance funds have been set up in different European countries (France, Germany, Iceland, the Netherlands and Switzerland).

Regardless of such measures, the question remains how geological risks should be approached when assessing potential projects. Correctly doing this is vital, because the outcome of a project is determined largely by geological parameters.

Towards fully addressing geological uncertainty

Techno-economic simulations will almost as a rule involve the input of experts. This allows to realistically develop tools such as decision trees that summarise when investment decisions are taken. Similarly, expert input is typically used for dealing with geological data gaps. Working with expert input requires specific methodology and awareness of likely pitfalls. When it comes to integrating geological uncertainty in techno-economic simulations, also the way the actors (historically) interact and approach a problem becomes important.

Consider the following geothermal example, which ends in either an incorrect or a very vague result. After setting up a model focused on the engineering aspects of a doublet system, the modeller decides to ask the geological expert to provide a best estimate on the temperature of the reservoir water and the expected flow rate. These are logical questions in his view, because these are his direct input parameters for calculating the profitability of the project.

The geologist will provide information, but at the same time complain that flow rates have been insufficiently measured, and that in general the available information is not complete enough to make reliable estimates.

What happens then largely depends on who is most convincing or stubborn: geological uncertainty is either not mentioned, or the end result of the whole study is considered as indicative only.

So how to improve this very typical situation? First it is important to understand what goes wrong: the modeller asks the wrong questions, and the geologist sees only uncertainty.

Geologists are very aware that their descriptions are based on very little information. This is especially true for deep geological settings, such as those for geothermal projects aiming at binary heat and power production.

What they do not realise is that economic methods are able to deal with exactly that: very large uncertainties. This is especially true for decision tree-based analyses, such as the real option approach that is used here. A best estimate does not have to be a value ± 20%; ± 2000% will also still work.

The modeller on the other hand sees only his data gaps, but should realise that questions should be properly formulated. Using expert data is very common and has scientifically been proven to be reliable, provided that certain rules are respected (e.g. Henrion & Fishoff, 1986; Bier, 2004; Lin & Bier, 2008; put into geological context by Welkenhuysen *et al.*, 2013).

Especially when it comes to geological information, an expert needs to be able to translate his view or idea regarding a specific part of the subsurface as directly as possible into input for the model. For geothermal energy, a correct approach is outlined in the following section.

But in general, the important lessons for making such an exercise work are: (1) 'modeller to geologist'– formulate questions for input with respect for how a geological expert understands the subsurface and its uncertainties, and (2) 'geologist to modeller' – specifically include uncertainty ranges, even when orders of magnitude are large, as they are the most essential part of the input.

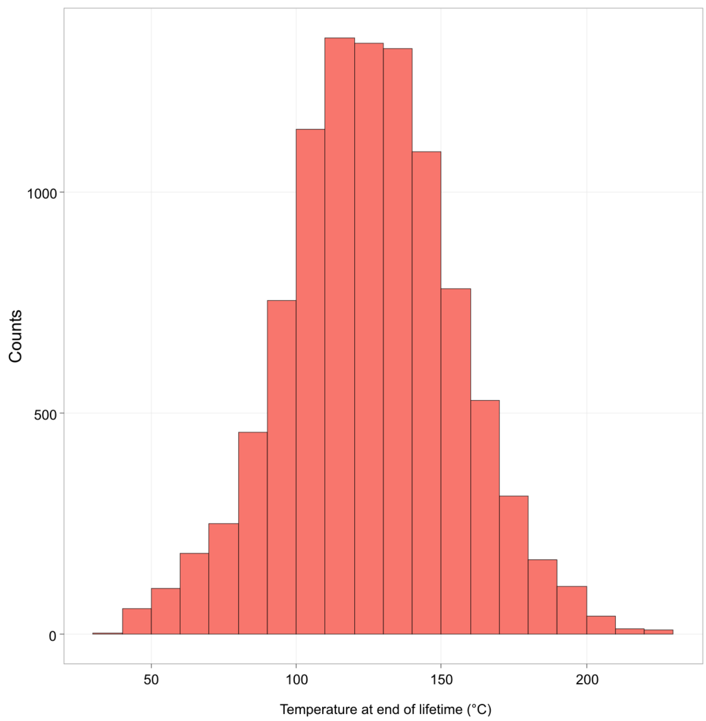


Figure 3: The uncertainty range of the temperature at reservoir depth includes the uncertainties on the temperature gradient, depth to the top of the reservoir and its thickness.

Approach applied to the Campine case study

This case study targets the geothermal reservoir of the Campine Basin: the Carboniferous Limestone Group. The reservoir concept is described by probabilistic distributions for 10 parameters that form the input of the geological model: the chance of geotechnical failure of the reservoir, depth, total thickness, productive thickness, the geothermal gradient, transmissivity, flow rate, effective porosity, distance between doublets and distance between wells.

Five independent experts from three institutes were consulted. All have an academic background in geology and are well acquainted with the deep geology of Belgium. Data were collected in spring 2016.

The probabilistic input of the different experts is combined by averaging with equal weights, assuming that each expert's opinion is equally valuable. The analytical model for geothermal heat recovery from doublet systems developed by Gringarten (1978) was used as the basis, and modified to allow for partially penetrating wells (Chang & Chen, 2003).

This model is used to stochastically calculate 100,000 realisations of the extractable heat and the optimal configuration of a single doublet system and a field of doublets. For each realisation the input parameters are sampled from the input parameter distributions. The reservoir's

Table 1: Distribution of outcomes over the different end-uses of geothermal energy.

Scenario	*Reference case*	*Subsidy case*
1) Failed	*80.3%*	*80.4%*
2) LT Heat plant	*0.0%*	*0.0%*
3) HT Heat plant	*19.7%*	*16.3%*
4) EGS & PP	*0.02%*	*3.0%*
5) Power plant	*0.01%*	*0.4%*

temperature (***Figure 3***), and optimal flow rate and depth are calculated by the model. It was decided to use an analytical model instead of a numerical model, in order to reduce calculation time for generating stochastic input parameters while still ensuring sufficient accuracy. The choice to calculate 100,000 realisations is made to test model performance (a secondary study objective). In practice this number could be an order of magnitude lower for this specific study.

Both models adopt a similar stochastic approach. The level of complexity of the decision tree is such that the geological model can be run independently from the techno-economic model. This means that all results of the geological model can be calculated prior to running the techno-economic model. This is not necessarily possible for more complex situations; such cases would requires integrating the two models.

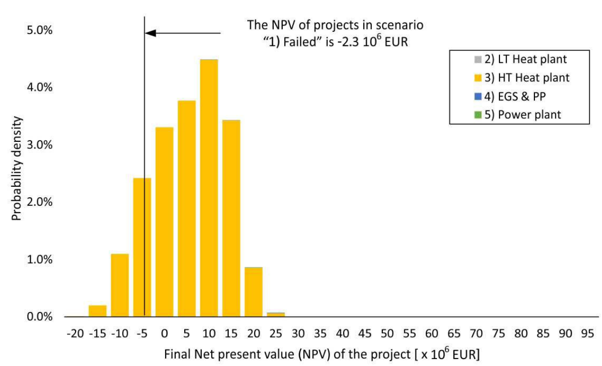
Case-study simulation and probability distributions

The first part of the research derived estimated probability distributions of the main subsurface parameters. Petitclerc *et al.* (2016) describe how the decision tree for a geothermal project development has been executed based on these distributions. These calculations are repeated for 50,000 runs to approximate the final distribution of outcomes.

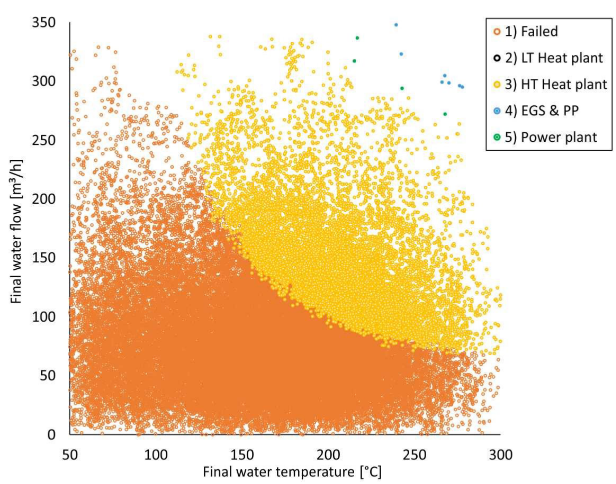
Two cases were tested:

- A reference case of a regular geothermal project without any public investment or subsidies to stimulate renewable energy production.
- A subsidy case where additional subsidies are granted only for renewable electricity production, for an amount of 250 EUR/MWh.

Reference case

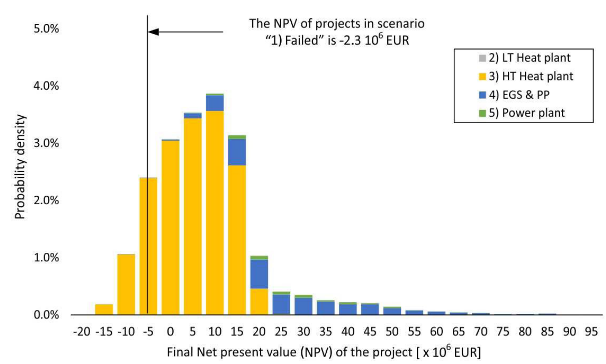


a. Histogram of the Net Present Values (NPV) of all successful outcomes for the reference case

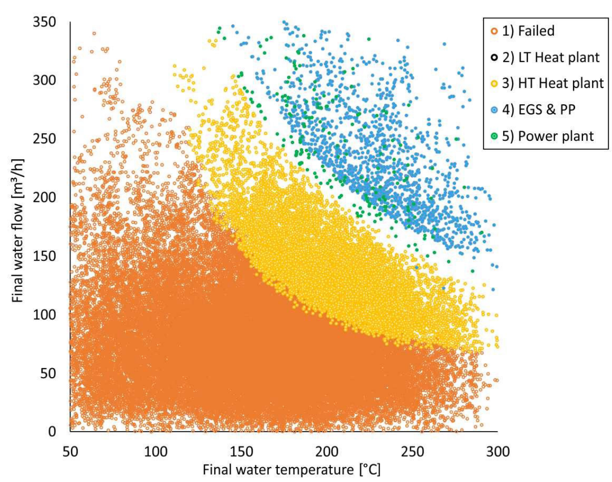


b. Distribution of all outcomes to the final water temperature and flow rate for the reference case

Subsidy case



c. Histogram of the Net Present Values (NPV) of all successful outcomes for the subsidy case



d. Distribution of all outcomes to the final water temperature and flow rate for the subsidy case

Figure 4: Reference and subsidy case outcomes. a and c: histogram of the Net Present Values; b and d: distributions of all outcomes according to the final temperature and flow rate.

The geological, economic and technical assumptions were kept identical. The subsidy scenario is a test case for the effect of electricity stimulating policies. The level of subsidy is similar to the subsidies granted for photovoltaic panels during the emergence of this technology.

The results in ***Table 1*** illustrate the distribution of outcomes for a project with a location similar to the Balmatt site before any new survey for the reference and subsidy case. These show already that over 80% of the projects do not survive the preliminary survey phase or the execution. The large majority of the remaining 20% of the projects are focused on delivering HT heat. When an added stimulus is created for the production of electricity, there is a moderate shift from HT heat to the power plants. However, the overall success rate of projects remains exactly the same. So the subsidy does not seem to change the overall success rate of the project. This finding intuitively seems difficult to explain, but, as is shown in the discussion, boils down to a simple rule: subsidies need to take into account geological reality.

Discussion

Reference case: no subsidy

In the reference case, most of the successful projects (19.7%) are HT heat plants. ***Figure 4a*** shows that even projects that are realised may still be faced with operating conditions that are insufficient to earn back exploration and investment costs. Failed projects in general end with a negative NPV of €-2.3 million, equal to the exploration costs.

The distribution of successful and failed projects in ***Figure 4b*** shows that successful projects require a good combination of geological conditions (temperature and flow rate). Power plants are only installed under highly optimal combinations.

Subsidy case: 250 EUR/MWh

When subsidies are granted for renewable electricity production, the amount of failed projects remains unchanged, and the distribution of NPV remains largely the same (***Figure 4c***). The main difference is the appearance of combined heat-power plants, skewing the histogram to the right. Electricity generation is attempted in cases with optimal combinations of underground parameters. These projects were already chosen for HT heat plants in the reference case, so the electricity subsidy allows the transformation of existing HT plants into heat-power plants.

Figure 4d shows more clearly how a subsidy on electricity production fails to pull this technology into the market, and instead only favours already profitable projects. This demonstrates that a subsidy needs to be tailored to the geological conditions. The subsidy fails because it is too improbable that geological conditions will, even with subsidies, allows power to be economically co-produced.

The study presented here clearly demonstrates that the choice of subsidy mechanism is crucial. Copying the method from another renewable energy source, in this case photovoltaic electricity production, where the subsidy has proven to work, is not a proper starting point. More appropriate policy instruments that take into account the geological conditions and uncertainties exist in neighbouring countries, such as geological or drilling risk insurance and recoverable advance for the feasibility phase. These two instruments, coupled with a feed-in tariff for electricity production, are currently recommended to stimulate the power geothermal sector development. This combination of measures adapted to the Belgian context will be evaluated in the near future.

Consistency check of geothermal parameters and reliability of the reservoir model

The experts were consulted in such way that a validation of the accuracy of the expert data and the analytical model was possible. Two parameters, flow rate and well distance, were estimated directly by experts and alternatively calculated from other parameters (***Figure 5***). Based on the assumptions for setting up the questionnaires, these are the calculated parameters that should be most reliable. Both can be compared in light of the recently obtained

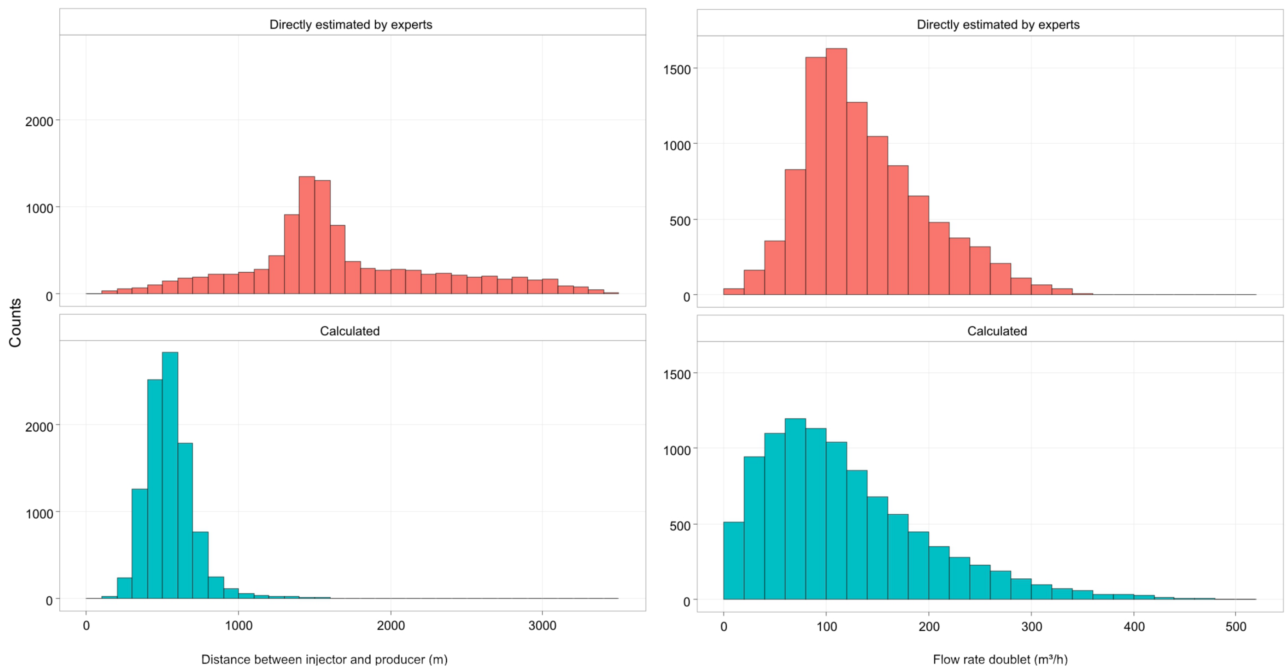


Figure 5: The upper histograms present the expert estimates on the distance between the doublet wells and the flow rate that can be achieved. The lower histograms present the results for the same parameters, but this time calculated indirectly from expert input. The significant difference for well distance is probably due to the definition of project life time, which was differently perceived by the experts than it is defined in the model.

pumping tests on the Balmatt wells.

A first observation is that for both flow rate and distance, the ranges of calculated results are about two times larger than those from the experts. The distribution of the calculated flow rate is more skewed than that of the experts. This is evident from the lower mode and the longer tail towards higher values. The single well pumping tests seem to indicate values towards the higher end of these distributions. Since these experiments indicate upper limits for flow rates, this seems to confirm that the calculated estimates are realistic.

A larger difference is observed for the well distances. The calculated distance is much smaller, to the point where it approaches unrealistic values. The mode is around 600 m, while the experts estimate it to be around 1500 m.

The difference is probably an unintentional side effect, and an example of the great care with which parameters need to be handled in these exercises. In the analytical calculation, the lifetime (35 years) is an average. The experts, however, intuitively perceived it as a safe minimum.

Preliminary sensitivity analysis has shown that lifetime (non- stochastic input parameter) needs to be multiplied by a factor of 8 in order to close the gap. This looks very high, but not impossible with the uncertainty ranges estimated here.

Uncertainty and the value of flexibility

In spite of what geological experts often assume, geological uncertainties can be very large without inhibiting conclusions regarding the potential outcome of projects. However, correctly addressing them does require an in-depth understanding of geological uncertainty, how it is being perceived, and how it is optimally translated for techno-economic modelling.

This does not imply that obtaining geological information is not useful; the contrary is actually true. Embedded in the decision tree is the assumption that additional data becomes available and uncertainty largely resolves as the different project stages are executed. Without such assumption, the simulation would show that geothermal projects would not be realised.

There is a fundamental difference between geological uncertainty – the focus of this paper – and market uncertainty. Under price uncertainty, investment is not a 'now or never' decision. The firm has an option to invest and there is value in waiting. If the firm invests, it kills the option to invest and it loses the flexibility to wait. In the economy, this represents a cost. In contrast, under geological uncertainty, investment creates flexibility: the investment in exploration reveals information and creates an exploitation option. This count as a revenue. Hence, market uncertainty postpones investment, geological uncertainty stimulates investment.

For a project dominated by geological uncertainty, it is highly relevant that all parties involved correctly understand such 'geology-specific' aspects in order to come to a correct understanding. The value of learning and the trade-off between market and geological uncertainty are only a few of the challenges in geological economics.

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