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The impact of policy measures on profitability and risk in geothermal energy investments

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Abstract
The development of geothermal energy is below the European National Renewable Energy Action Plans' anticipated trajectory. High upfront investment costs and multiple sources of uncertainty result in a major investment risk, hampering the mobilization of required capital. To evaluate different policy measures, we developed a geological economic Monte Carlo simulation model that integrates both market and geological uncertainty and a firms' option to abandon the geothermal project development after a first drilling is made. If the objective is to reduce the abandonment rate of geothermal projects, a heat premium comes forward as the most cost-efficient policy instrument. However, the risk that a project turns out unprofitable is not reduced and windfall profits do occur. In contrast, a recoverable loan reduces both the investment risk and the abandonment rate. An insurance scheme targets the investment risk as well. However, it also increases the abandonment rate and appears as the least cost-efficient policy measure. Considering the different policy performance indicators, a tax rebate is never preferred. Our results demonstrate the intricacies of choosing the correct policy measure, and the need to support such policy decisions with quantitative analyses.

Keywords: deep geothermal, heat production, project abandonment, decision tree, uncertainty, Monte Carlo

1 Introduction
Renewables are considered to be a crucial driver in the decarbonization of the energy system, spurring innovation and increasing energy efficiency and energy security. According to the latest Renewable Energy Progress Report of the European Commission (2017), in 2014 the EU was on track to meet the 2020 binding targets on renewable energy deployment. Geothermal growth, however, is below the National Renewable Energy Action Plans' anticipated trajectory. Geothermal energy production has a small carbon footprint, the ability to provide continuous power and heat and its implementation can be made responsive to grid unbalance (IRENA, 2017). Furthermore, it is considered as an abundant energy resource, being preferred over scarce fossil fuels which are more valuable for the production of goods other than energy (Santiago et al., 2014). Despite its environmental and economic benefits and opposed to most other renewables, in the EU only 3% of the economic potential of 174 TWh in 2030 is currently utilized (Van Wees et al., 2013), indicating a large scope for growth in the sector (Sigfusson and Uihlein, 2015).

Geothermal energy is derived from the thermal energy generated and stored in the Earth's interior. There are many variants of geothermal energy production which can broadly be categorized into shallow and deep applications. Shallow geothermal energy is almost everywhere available and ground source heat pumps are commonly used to convert the low temperature geothermal energy to a higher temperature for space or water heating. Deep geothermal wells can either tap into permeable water-bearing strata, aquifers (hydrothermal systems), or impervious rocks can be fractured to obtain sufficient permeability (enhanced geothermal systems). Whereas shallow geothermal projects are relatively low in risk and capital cost, deep applications have a high upfront investment cost and a high risk on failure (European Commission, 2017; Sigfusson and Uihlein, 2015).

Consequently, one of the main barriers to the large-scale uptake of geothermal energy is financing. Due to exploration costs, drilling of production and injection wells, field infrastructure, geothermal fluid collection and disposal systems, the costs associated with the energy plant, grid connection costs and other project development costs, geothermal deployment involves substantial investment costs and a large part of this capital is required before confirmation of resource exploitability and hence project profitability (IRENA, 2017).

Furthermore, the geographical distribution of heat flow and fluid permeability within the Earth's crust is highly variable. The risk of failure originates from unknown subsurface conditions and rock properties (Vogt et al., 2013). Uncertainty is present in the initial aquifer state (e.g. pressure, salinity, presence of gasses), at reservoir level (e.g. rock and fault permeability), and in operational parameters (e.g. flow rate and re-injection temperature) (Daniilidis et al., 2016). Therefore, numerical models are developed to analyse the impact of these geological uncertainties on geothermal output (Saeid et al., 2015; Vogt et al., 2013) and energy output (van Wees et al., 2012) for generic evaluation or prior to further exploration.

To ease the financial barriers, reduce uncertainty and stimulate geothermal development, a variety of policy support measures can be adopted. The main support system to promote renewable electricity production within the EU is the feed-in tariff which is a fixed and guaranteed price paid to the eligible producers of electricity from renewable energy sources (EGEC, 2013). Also to finance renewable heating and cooling projects, feed-in tariffs and feed-in premiums (i.e. a guaranteed premium in addition to the revenue resulting from selling renewable energy) are considered as the mainstream public support tools (FROnT, 2018). Whereas feed-in tariffs and premiums are designed to increase the overall profitability of the geothermal project, certain support schemes specifically incentivize the mobilization of risk capital at the exploration stage (Sanyal et al., 2016). In some cases, the government acts as the project developer and operator and takes on the full resource and project risk or the government shares the exploratory drilling costs with a private developer in order to catalyse private funding for the larger portion of the development. In other cases a geothermal resource risk insurance fund is established. Exploration risks are then pooled across a portfolio of development projects by insuring the productivity of a well prior to drilling. If certain pre-specified goals are not achieved, all or part of the losses are covered. Because geothermal is globally a small sector, the risks are not well absorbed (i.e. levelled out across undertakings). Furthermore, the high degree of uncertainty during the exploration makes the insurance premiums often unaffordable for developers. In this context, France, The Netherlands, Germany, Iceland, Switzerland and the Flemish region in Belgium have taken action to settle a national insurance fund (GEOELEC, 2013). Also, fiscal incentives such as tax rebates can mobilize capital as the upfront cost of geothermal exploration is reduced (Sanyal et al., 2016).

Recent studies that investigate the overall impact of uncertainty on investment in geothermal energy address uncertainty mainly by performing a Monte Carlo sensitivity analysis. Lentsch and Schubert (2014) focus on the well construction process and present a detailed approach to create a probabilistic model to evaluate the impact of geo-technical uncertainties and risk on the timing and costs of the well construction. Lukawski et al. (2016) also characterize the uncertainty that is associated with the completion and drilling costs of geothermal wells. They find that the median geothermal well cost increases exponentially with depth. Walraven et al. (2015b) consider an entire geothermal project and optimize an air-cooled organic Rankine cycle (ORC), powered by geothermal heat. They show that brine inlet temperature and annual electricity price evolution have a strong influence on the configuration and efficiency of the ORC and its economic feasibility. Van Wees *et al.* (2012) develop a tool to evaluate a geothermal direct heat application which takes into account geological, technical, and economic uncertainty through a sensitivity analysis. Their model calculates variations in doublet power performance and economic performance given uncertainty in geological and technical parameter values. Also, Willems *et al.* (2017) integrate geological, technical, and economic data to evaluate how well spacing affects the Net Present Value (NPV) of heat production from a hot sedimentary aquifer. Similar to Van Wees *et al.* (2012), a sensitivity analysis shows how both technical and economic data affects the Net Present Value of the geothermal project. They find that variation of the temperature difference between injection and production water and the production rate has the most impact on the NPV.

Besides uncertainty, these authors also take into account some form of governmental support. Van Wees *et al.* (2012) included an energy investment tax deduction and direct funding from the government. Willems *et al.* (2017) take into account an insurance cost and a feed-in tariff. Their sensitivity analysis shows that next to variations in the capital expenditure, also variations in the level of the feed-in tariff highly affect the NPV. Weijermars *et al.* (2017) do not make a techno-economic assessment but describe the successful development of a geothermal reservoir in the US. One of the key factors that ensured the participation of private equity partners was a mix of policy support instruments, including a federal loan, a loan guarantee, a tax credit and a cash grant. Policy support is most often part of existing investment analyses, however, the impact of these policy instruments on investment risk is not studied. Gross et al. (2010) point out that the detailed design of policy is important because policy instruments vary in terms of the risks that they mitigate. It is therefore vital to analyse the ability of policies to deliver investment and hence, to assess the relationship between policy developments and investment risk.

Deep geothermal projects are necessarily large scale, have a development process that spans several years, and have high risk. Risks stem from policy changes or economic, geological and technological uncertainties. As a consequence, practical initiatives for new projects are not always followed through. A first drilling is always required to confirm the size, temperature, flow, pressure, chemistry, and potential production rate of the resource which makes it difficult to mobilize private capital. Even then, a certain level of uncertainty always remains and success is not guaranteed (Franco and Vaccaro, 2012). There exist several examples in Europe, the US, and Australia where geothermal project developments are initiated but are put on hold or cancelled because of induced seismicity or collapsing wellbores. Moreover, other geothermal energy projects are abandoned after a successful drilling. In these cases, the first drillings indicated a low flow rate or a small porosity, which – combined with insufficient demand, or a lack of political support – proved that direct heat production was not economically viable (Sigfusson and Uihlein, 2015).

The integration of uncertainty and managerial flexibility to study policy implications for investments in carbon abatement technologies is not new. Mo et al. (2018) for instance analyse the investment in carbon capture and storage taking into account cost and price uncertainty, and a firm's flexibility to change the operations of the system. Ritzenhofen and Spinler (2016) study the optimal design of feed-in tariffs to stimulate investment in renewable energy by taking into account policy uncertainty and the firm's flexibility to wait and postpone investment. For geothermal energy deployment however, it is the managerial freedom *to abandon* the project during execution which strongly affects the estimated value of the project at the start. It is logical in practice, given the high-risk environment, that new projects for deep geothermal wells are subject to modifications during execution. Currently, there is rather limited analysis that incorporates this managerial freedom in technological or economic models, and that analyses the impact of such freedom on the effectiveness of public policy instruments. Furthermore, the investment risk of a geothermal energy project is highly determined by geological uncertainty.

This work is a first step towards including this essential element of the development of geothermal projects in a combined geological, economic and technological model. The work presented in this study adopts an interdisciplinary approach and combines geological data with economic decision-making to model the impact of both geological and market uncertainty on investments in geothermal energy production. We included managerial flexibility by integrating the option to abandon the geothermal project after the survey stage of the development process.

A study, most similar to ours, is the one by Daniilidis *et al. (2017)*. They integrate geological, technical and economic data, include different geothermal development stages, and take into account an early abandonment of the geothermal project in case of well failure. Similar to the previously mentioned studies, they analyse which economic, geological, and technical parameters affect the techno-economic performance of a deep geothermal heat system the most. Our study continues this analysis by integrating geological, technical, and economic uncertainty simultaneously in the economic assessment by means of Monte Carlo simulation and calculating the probability that a project is ceased and abandoned after the first drilling is made. Furthermore, this is the first study that models different policy instruments and calculates their impact on the reduction in abandonment rate, the expected project value to a private investor and the associated costs to the public authority.

The model is applied to a case study in the Campine region, Belgium. Currently, deep geothermal energy appears to be on the edge of a take-off in Belgium. 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 financed by the Belgian Science Policy Office, investigated the regional potential for geothermal heat and electricity production (Petitclerc *et al.* 2017).

Section 2 introduces the case study for which the analysis is made. The methodology, the different types of uncertainty, and the simulation of the project scenarios, is explained in Section 3. In Section 4, first the model outputs in terms of technical and economic performance excluding any policy measure is discussed. Next, the simulation of different policy instruments is described and we discuss their impact on the model outcomes.

2 Case study: Campine Basin

The Belgian subsurface presents an exceptional geological diversity resulting from tectonic events and the evolution of different sedimentary basins for a period of 542 million years. The sedimentary basins in the northeast (Campine Basin) and south (Mons Basin as extension of the Paris Basin of Belgium, and the deformed sedimentary basins now forming the Namur parautochton and the Dinant synclinorium) provide the most obvious potential for deep geothermal energy. This case study focuses on the Campine Basin, which is an intermediate basin between the Brabant Massif and the Roer Valley Graben, the latter an eastward extension of the active Lower Rhine Graben primarily within the Netherlands. The recognized geothermal resources and hydrothermal processes observed in the Campine Basin are localized in the thick sequences (up to 500 m) of Devonian to Lower Carboniferous (up to early Mississippian) platform carbonates, in North-West European stratigraphy referred to as as Dinantian, the primary geothermal target. Subaerial exposure prior to late Mississippian to early Pennsylvanian sedimentary deposition, corresponding in Europe to the Namurian stage, led to karstification along pre-existing fault zones and abundant collapse structures in the top tens of meters of the reservoir (Dreesen et al., 1985). Widespread Cretaceous chalks have also medium to shallow geothermal potential across much of the north of Belgium.

Much of the knowledge of the subsurface of Flanders comes from seismic surveys undertaken since the 1950's and exploration wells associated with coal exploitation. In 2015 a deep geothermal project was initiated at the Balmatt site near the village of Mol. At the time of writing three wells have been drilled, reaching depths between 3610 m and 4235 m, targeting the karstified Lower Carboniferous strata. A pumping test for the first (production) well revealed a production temperature of up to 128°C and a flow rate of 140 m^3/h (Bos and Laenen, 2017). The simulated reservoir and project in the current paper are based upon this Balmatt project and target reservoir, providing a realistic approach on project development.

Figure 1. Map view of the occurrence of Carboniferous Limestone Group (blue area) at depth in the Campine Basin, Belgium. These strata form the geothermal target reservoir in this study. A recent deep geothermal project was installed near the village of Mol.

3 Materials & methods

To analyse the investment problem, we take the viewpoint of a private investor. This investor analyses one single case study to be executed in the defined region. A geological economic spreadsheet model is built to assess the feasibility of a deep geothermal project. In brief, this model consists of an analytical reservoir model using expert input as its main data source which is run in advance, and a techno-economic Monte Carlo-based project simulation, with different sources of uncertainty (geological, technological and market) and a decision moment after drilling the first well. The decision is based on the expected output and project revenues and simulates managerial freedom. The choice that can be made is either abandoning the project or installing a heat or power plant in different configurations.

The impact of several policy instruments, and their combinations, is considered. The individual parts are further elaborated in the next sections.

3.1 Reservoir model and geo-technical uncertainty

The deep geothermal reservoir is represented by an analytical geotechnical model for a single geothermal doublet system, based on Gringarten (1978), targeting the Carboniferous Limestone Group of the Campine Basin. The geotechnical input parameter values and their uncertainty distributions are obtained through an expert questionnaire, of which the concept is shown in Welkenhuysen et al. (2013). Expert input can be used as a valid data source if collected and processed properly (Bier, 2004; Henrion and Fischhoff, 1986; Lin and Bier, 2008). Using the expert input on a basic reservoir concept allows for fully describing a reservoir and incorporating all uncertainties that are at hand, without the need for highly detailed traditional data.

Five independent experts from three Belgian institutes were addressed for the current exercise: three experts from the Geological Survey of Belgium, one from VITO (Flemish institute of technological research), and one from the University of Mons. All experts have an academic background in geology and are well-acquainted with the deep geology of Belgium. Experts were free to indicate whether they had sufficient knowledge for making judgements. Data was collected in spring 2016, and none of the experts were directly involved in the setup of the methodology and the processing of results. The experts had to provide their estimation of the probability distribution regarding following 10 model parameters:

- geotechnical probability on reservoir failure (single number)
- depth of production
- total thickness
- productive thickness
- geothermal gradient
- fluid transmissivity
- flow rate
- effective porosity
- optimal distance between the wells

The probabilistic input of the different experts is combined by averaging with equal weights, assuming that every expert opinion is equally valuable. Once the average probability distributions of the geological parameters are determined, the probability distribution of the production characteristics for the well are calculated. The analytical model for geothermal heat recovery from doublet systems developed by Gringarten (1978) was used as a basis, and modified to allow for partially penetrating wells using the work of Chang and Chen (2003). With this model, the extractable heath and optimal configuration of a single doublet system and a field of doublets can be calculated. We turned this model into a stochastic model for a single doublet system by randomly varying the input values as supplied by the averaged expert input distributions. Known and unknown correlations between input parameters are maintained by using a single random value for every parameter within a single Monte Carlo iteration. In total, 100 000 Monte Carlo iterations were performed. Because of redundancy between the expert input and model result parameters, a cross-check was possible to ensure consistency of and confidence in the reservoir data (see also Petitclerc *et al. (2017)*). This geothermal model results in probabilistic distributions of depth, temperature, and flow and are used as input for the techno-economic Monte Carlo-based simulation. Table 1 shows a summary of the modelled reservoir data. Raw expert input data and the geotechnical model itself are available upon request from the corresponding author.

	Average	Standard deviation	Minimum	Maximum
Depth (m)	3537	298	2676	4523
Distance between wells (m)	550	171	138	2120
Flow rate (m^3/h)	107.7	74.8	0.2	506.0

Temperature (°C)	125.4	29.5	36.5	223.9

Table 1. Summary of the reservoir data. Carboniferous Limestone Group of the Campine Basin, Belgium

Dealing with underground resources inherently comes with uncertainties as processes and properties can never be mapped with absolute certainty. In our model, geo-technical uncertainty is clustered in two sources:

- Geological uncertainty: uncertain outlooks of well distance, depth, temperature and flow as presented in Table 1.
- Drilling risk: an additional cost due to unforeseen circumstances during drilling.

The geothermal properties and associated well configuration are therefore different in the exploration or operational stage by applying limited foresight ((Welkenhuysen and Piessens, 2017); see further under 3.3 Project simulation). There are also significant risks on complications while drilling. Borehole collapses or loss of drilling equipment may lead to significant delays or force the team to repeat a part of the works. Experts indicate that this risk can be accounted for with a top-up cost above the standard drilling cost of 1500 €/m as an additional stochastic cost with a normal distribution (mean: 1000 €/m, standard deviation: 200), with a 30% chance of occurring.

In real-world projects, geothermal project developers have to make investment decisions taking into account these multiple geo-technical uncertainties. To reduce uncertainty, a geothermal investment project runs through several exploration stages, starting with a geological survey and ending with a pumping test before the operational stage. At each stage additional information becomes available and uncertainty in the parameter values is reduced. Besides geo-technical uncertainty, geothermal projects also face market uncertainty.

3.2 Market uncertainty

Besides geo-technical uncertainty, also market uncertainty affects investment behaviour. The fluctuation of market prices for low- and high-temperature heat and electricity are modelled as a Markov chain with drift (Eq. 1).

$$p_t = p_{ref} * (1 + T_{rand})^t + V_{rand} \qquad \text{(Eq. 1)}$$

Where p_t is the price at a given time t (€/MWh), p_{ref} is the reference price point (€/MWh), T_{rand} is the long-term market trend with random behaviour, and V_{rand} is the short-term variation with random behaviour. This approach allows to account for short-term fluctuations, and long-term trends divergent from standard inflation. Both T_{rand} and V_{rand} are assigned a normal parent distribution with parameters shown in Table 2.

	p_{ref}	μ T_{rand}	SD T_{rand}	μ V_{rand}	SD V_{rand}
Low Temperature heat (<90°C)	20	0.0	0.001	0	6
High Temperature heat (>90°C)	30	0.0	0.001	0	9
Electricity	140	0.0	0.001	0	42

Table 2. Parameter values (in €/MWh) for simulating energy price fluctuations.

3.3 Project simulation

The presented geological economic method comprises two interlinked parts: a geotechnical model as described in Section 3.1, and a techno-economic Monte Carlo-based calculation of a single project, elaborated here. Current techno-economic calculations for geothermal energy deployment are often deterministic in nature. Uncertainties are usually addressed in a separate sensitivity analysis, but there is no real measure of financial risk, nor is there an option to alter the project along the way to maximise profitability. The inclusion of several options introduces the flexibility to deal with uncertainty. A theoretical framework of such Real Options Analysis was developed by Dixit & Pindyck (1994), and while not applied in its full extent here, the intricacies and consequences of optionality are included in our model. To simulate realistic decisions under uncertainty, the outlook towards the future should be uncertain as well. Combining such limited foresight with the optionality creates a model which approaches real-life circumstances much closer (Welkenhuysen and Piessens, 2017).

Optionality in a decision tree distinguishes a development in distinct steps. Under different circumstances, different decisions are taken, and new pathways are chosen, based on the results of the previous step. The main advantage of the decision tree over standard discounted cash flow calculation is to incorporate the flexibility that the investor has to redirect or abandon the project during the development process. Different risk factors affect the investment decision in different ways. Compared to a static analysis that does not include risk, the inclusion of risk factors in an investment analysis may re-order the relative attractiveness of the various investment options faced by an energy company (Gross et al., 2010).

The techno-economic model of a single geothermal doublet system in the defined region simulates cash flows through time, with an exploration phase of 5 years, and an operational phase of 35 years. The equations of the full model can be found in Annex A. The exploration phase includes reservoir exploration and drilling of the first well. Exploration investment is calculated according to Equation 2. Figure 2 shows a schematic representation of the calculation workflow.

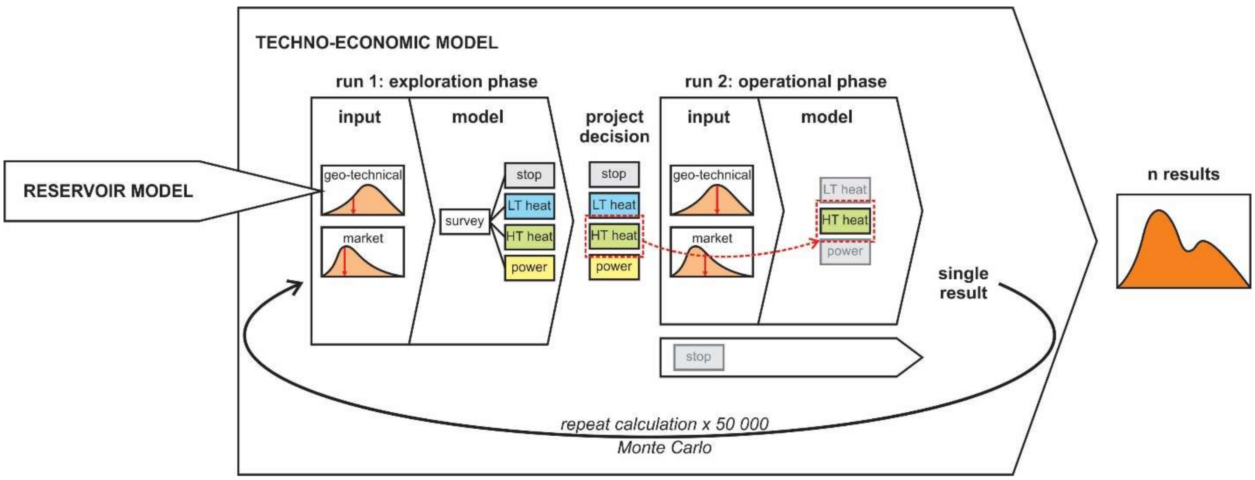


Figure 2. Schematic representation of the calculation workflow. In a first model run, as a future outlook, one random set of the stochastic parameters is used for the calculation. This results in a preferred operational scenario for those circumstances and the decision to either abandon the project or start the operational stage is made. To produce the actual result, a different random set of the stochastic input parameters is drawn in a second model run and the expected NPV of the selected operational scenario is calculated. Note the difference in random parameter values between the exploration and operational phase. This process is repeated in a Monte Carlo calculation resulting in probabilistic distributions.

$$I_E = \frac{-500\ 000\ €}{(1+r)^2} - \frac{500\ 000\ €}{(1+r)^2} - \frac{Dept\ \ *1\ 500\frac{€}{m}}{(1+r)^3} \quad \text{(Eq. 2)}$$

Where r is the discount rate, the first term is the cost for exploration in year 2, the second term is the cost for borehole design in year 2, and the third term is the first drilling cost in year 3, depending on depth. This cost is subject to the drilling risk (see section 3.1 Reservoir model and geo-technical uncertainty).

At the end of the exploration phase, during a first model run, a simulation or "outlook" is created of the expected cash flow of the operational phase. This is based on a single random draw from the probabilistic distributions of the reservoir output and probabilistic economic parameters. An expected NPV is calculated for four project scenarios: (i) project abandonment, (ii) a low-temperature (LT) application, (iii) the combined development of a high- and low-temperature (HT/LT) application, or (iv) electricity production combined with a high- and low-temperature application (E/HT/LT). Based on the outcome, the scenario with the highest NPV is chosen.

Abandonment leads to a loss of expenses made, and unless chosen, the operational phase starts with the second drilling for the doublet system and continues with actual operation.

The investment for the second drilling in year 4 is calculated as shown in equation 3.

$$I_D = \frac{-Dept \ \ *1\,500\frac{€}{m}}{(1+r)^4} \qquad \text{(Eq. 3).}$$

Where r is the discount rate. The same stochastic risk factor from the first drilling is applied to this second drilling cost.

The investment cost of the heat plant in year 5 is assumed constant and equals I_{HP} = 1 110 000 Euro. We consider cascaded use of energy. When the geothermal energy project is further developed for electricity production, both an electricity plant and a heat plant are installed. The investment cost of such a binary power plant is based on (Walraven et al., 2015a) and the cost per unit of electrical energy output decreases with increasing capacity with a minimum of 3000 €/Q_{el}:

$$I_{pp} = \frac{-I_{HP} - Ma \ \ [3000Q_{el}\,;(13\,000 - 60Q_{el})Q_{el}]}{(1+r)^5} \qquad \text{(Eq. 4)}$$

Where I_{HP} is the investment cost for the heat plant (€), Q_{el} is the extracted heat for electricity production (MWh) and r is the discount rate.

For the selected scenario, an NPV calculation is made with a new, second draw from the probabilistic parameters. Opposed to the first "outlook" calculation, this second one is considered as "reality". The final project value is obtained from this calculation, considering the operational scenario that was selected in the "outlook". In the second "reality" calculation, the stochastic parameter values have changed due to knowledge gained during exploration. The project NPV is calculated as shown in equation 5.

$$NPV_i = \sum_{t=5}^{40} \frac{\sum_k Q_{i,k} * p_{t,k} - OC}{(1+r)^t} - \sum_{t=5}^{25} \frac{PPMT + IPMT}{(1+r)^t} \qquad \text{(Eq. 5)}$$

Where i refers to the selected development scenario (LT, HT/LT, E/HT/LT), k is the type of energy output (LT, HT, E), Q is the heat flow (MWh), p is the energy price (€/MWh) which is subject to market uncertainty (see Section 3.2 Market uncertainty), OC are the operational costs (€), PPMT are the annual principal costs for a loan (€), IPMT are the interest payments for such a loan (€) and r is the discount rate.

This two-step approach thus uses different stochastic input values for both model runs. This difference between outlook and real parameter values simulates limited foresight, resulting in an outlook-based decision that can deviate from the optimal decision for the circumstances that occur in the operational phase (see also Welkenhuysen & Piessens, 2017). This method approaches real-life circumstances closer compared to a deterministic system. This also means that projects that were evaluated positively during the exploration phase, may result in an economic loss during actual operation because of a non-optimal decision.

To calculate the NPV, we consider a period of 5 years for explorations and the construction of the plant and 35 years for the actual operation. A discount rate of 10% is applied. All costs and benefits are calculated on an annual basis. Details of all elements that are included in the calculation are described in Annex A.

Because of the complexity of dealing with multiple uncertainties and decision-making, the robust Monte Carlo calculation method is used to account for the uncertainties. The calculation of the full techno-economic model, both exploration and operational phase, is repeated 50 000 times, with random sampling from the reservoir simulation results.

Running the techno-economic model with a decision step in a stochastic way enables calculating the probability that the project operates under the LT-operation, the HT/LT operation or the E/HT/LT operation and its probability of success, i.e. the probability of a positive NPV. Additionally, the abandonment rate, the expected private value to the project developer and the expected public cost (in case of public support, see further) are analysed.

One simplification in the analysis is that the first drilling will always take place after which we only assume one point at which the geothermal energy project can be abandoned. Also, the degradation of the geothermal resource during the plant operation is not considering other than through assuming a limited life time. Therefore, future research should make the different project development stages and the different actions that can be taken at each decision node more explicit within the analysis.

3.4 Simulation of Policy Measures

First the calculations are made without governmental support. Then, different policy instruments are integrated in the analysis. These policy measures are considered as external factors that change the investment cost or incoming and outgoing cash flows. We also analyse the occurrence of windfall profits, the effectiveness of each policy measure in reducing risk, and how much added value is created for the private geothermal developer. We simulate four policy instruments: a recoverable loan, a heat premium, a tax rebate and an insurance system. Equations for integrating these support mechanisms in the economic calculation are given in Annex A. The recoverable loan is an advantageous loan that is provided by public institutions. The advantage of the loan is that capital reimbursements can be reduced when the project does not earn enough to pay for its monthly capital reimbursements. In that case the specific reimbursement is covered by the government. This policy instrument is a typical example of a cost-sharing support tool by which also the risk of the geothermal development is shared between the government and the private developer. The recoverable loan is modelled at both the exploration and development phase.

A second policy instrument considered is a heat premium. For each MWh of geothermal heat produced, the firm receives a fixed premium. Hence, this policy instrument is only applied if the firm does not abandon the geothermal project after the first drilling and a specific development scenario is selected.

The federal tax rebate is a system that is currently available for investments in sustainable energy production and consumption. With this system, the company can claim a percentage of the sustainable investment cost in the annual tax declaration on top of the declared investment cost, and thereby reduce the taxable income. As the tax rate in Belgium is currently 33.99%, this system is equivalent to a reduction in the total investment of 33.99% of the part of the investment cost that can be booked additionally.

Because the risks related to a geothermal project are very high, insurance companies are not likely to provide standard insurance services for these projects. The operational expenses for an insurance of a large deep geothermal plant are impossible to obtain or very expensive, given the fact that very few installations of this type have already been created. First, we model an insurance which pays back the first drilling for 90% in case the selected scenario is 'project abandonment'. If the project is activated after the first stage, but the operation results in a negative NPV, then the second drilling is reimbursed for 90%. Note that unlike the previous policy measures, the public insurance will not only result in a benefit to the private investors. This measure also involves a cost, namely the premium that needs to be paid to be insured. Hence, the difference in premium level affects the expected private value and has no impact on the public contribution. We consider a premium level of 1%, 10%, or 20% of the drilling cost.

4 Results & discussion

The development of deep geothermal energy projects is lower than foreseen by the 'National Renewable Energy Action Plans' of different EU countries. The main barriers to large scale uptake are the high upfront investment cost and the geo-technical uncertainty. Only after the first drilling is made - and capital is spent - uncertainty in the value of geo-technical parameters is significantly resolved. Based on the results of such a first drilling, a developer could decide to abandon the project if the drilling proves that geo-technical parameters are too low to ensure the economic viability. For the described case study, we calculate the probability that the geothermal energy project is abandoned after a first drilling in case there is no policy support, and we determine the expected project value for the different scenarios considered. Then, we analyse how cost-effective different policy instruments are in (i) decreasing the abandonment rate, (ii) avoiding windfall profits, (iii) reducing the probability that a continued project results in an economic loss, and (iv) creating added value for the project developer.

4.1 Geothermal energy deployment without policy measures

Note that this geological economic model does not determine the probability that a geothermal project is started. It considers a geothermal energy project that is under development, *i.e.* the decision to start exploration has been taken, and takes into account the flexibility to abandon the project at an early stage. We analyse the probability that a geothermal energy project is abandoned after a first drilling is made and if the project is continued, which type of geothermal application is most likely to be selected. The performance of the geothermal project in terms of temperature, flow, and net energy output (GWh/y) are shown in Figure 3. The net energy output is a direct result of two stochastic reservoir parameters: temperature and flow rate. It consists of the net low- and high-temperature heat output supplied by the geothermal plant, excluding conversion to electricity, when applicable.

The reservoir model provided 100 000 combinations of reservoir parameters, including temperature and flow rate. This dataset is subsampled 50 000 times by the geothermal project decision model to generate the presented results. When these subsampled reservoir parameter values are tied to the model's project decision outcome, it can be determined how a project develops given specific circumstances. In Figure 3, the projects in the reference scenario that are abandoned after the first drilling are shown in red, in green the projects that become active. In grey the total of the 50 000 subsamples is shown. For both temperature and flow rate, lower values more often lead to project abandonment. In comparison with the flow parameter, the ranges for abandonment or activation for the temperature parameter have a large overlap. This difference is also apparent from the distributions' averages, with 117°C versus 134°C for temperature, and 56 m^3/h versus 121 m^3/h for flow rate, for abandonment and activation respectively. This indicates that the choice for abandonment or activation is more sensitive to the flow rate. This observation is in line with the sensitivity from Daniilidis et al. (2017) and is confirmed by oral communication with operators in the field.

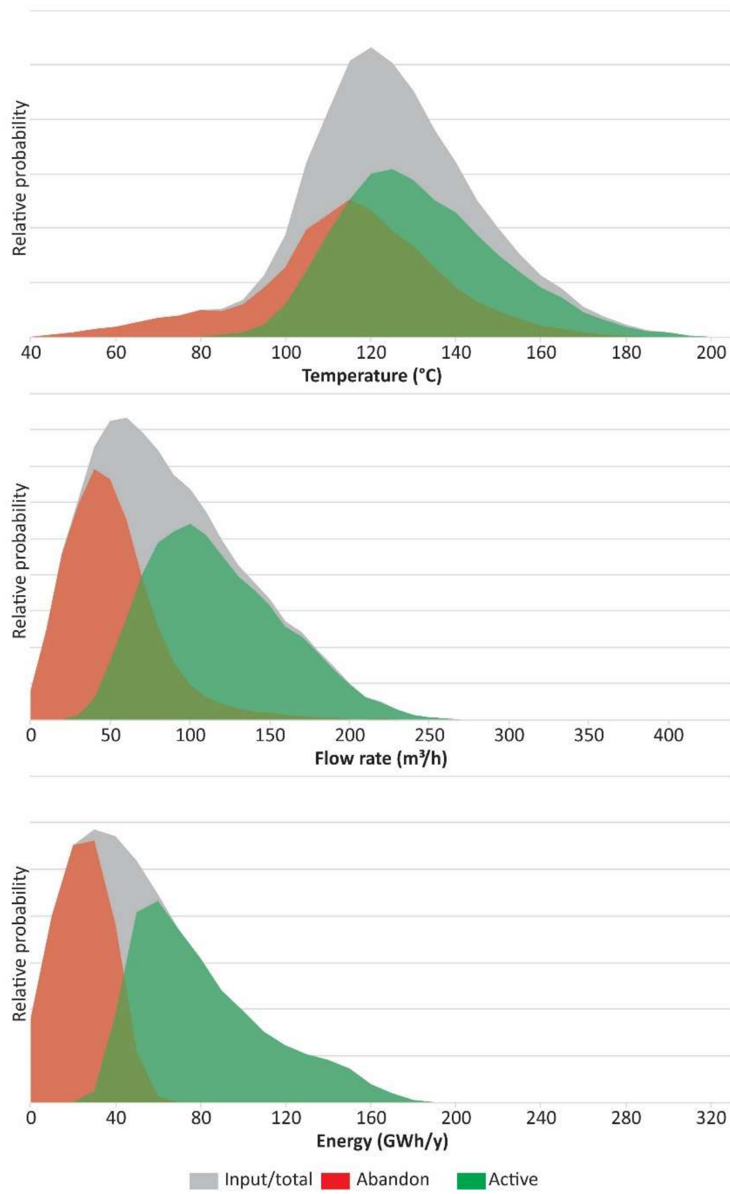


Figure 3. Distribution of the stochastic values for reservoir temperature (grey, total), and of the projects that are either abandoned (red) or activated (green).

Table 3 gives an overview of the probabilities with which a specific scenario occurs and the corresponding average NPV. The NPV probability distribution of the abandonment scenario and the HT/LT scenario is shown in Figure 4 (left and right respectively). Without any support system, there is a 45% probability that the project is abandoned after the first drilling. This entails an irrecoverable sunk investment cost for the investor of 6.5 M€ on average. There is 55% probability that the geothermal energy project enters the second stage and is further developed. These active projects are almost exclusively plants that produce heat for both low and high temperature applications and have an expected project value of 6.8 M€. Table 3 shows that there is only a 35% probability that a fully developed geothermal energy project is successful in the sense that it is continued after the survey stage and that it obtains an NPV that is equal to or larger than zero. There is 19.55% probability that a geothermal project is continued and that its operations result in an economic loss. A plant for only low temperature applications is selected in a negligible 0.1% of all cases.

Furthermore, it is most likely that the LT geothermal project turns out to be economically unfeasible. The binary power plant scenario is never selected. On average, the expected value of a geothermal energy project is 0.8 M€.

	Probability	NPV	Public contribution
(1) Abandon project	45.27%	-€ 6,447,272	€ 0
(2) LT Heat	0.10%	-€ 6,121,965	€ 0
NPV<0	0.09%		
NPV>0	0.01%		
(3) HT Heat	54.63%	€ 6,780,975	€ 0
NPV<0	19.55%		
NPV>0	35.08%		
(4) Binary power plant	0.00%	€ 0.00	€ 0
NPV<0	0.00%		
NPV>0	0.00%		
Expected average project value		€ 779,896	€ 0

Table 3. Probability that a geothermal project is abandoned or continued into a specific application and the corresponding NPV

Figure 4 shows that the distribution of the abandonment value is much narrower than the distribution of the value of the HT/LT-application. This indicates that the option to abandon the project after the first borehole is capable of eliminating a defined set of unprofitable projects. However, this does not eliminate all risk, as operational, geological and market risks remain after this stage, and the final project may still be unprofitable despite of the positive estimation after the first drilling.

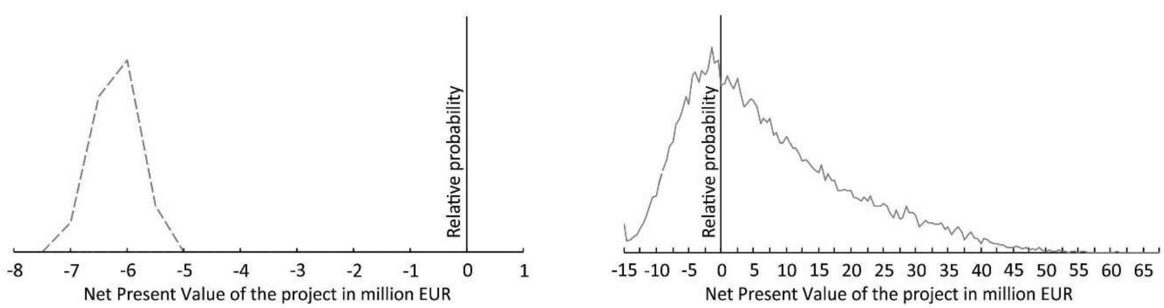


Figure 4. NPV probability distribution of abandoned projects (left) and projects that develop into HT/LT projects (right). Populations is 100 000 and bin width is 0.5.

4.2 Geothermal energy deployment with public support

We evaluate the impact of each policy instrument based on four performance indicators. First we analyze at what cost different policy measures reduce the abandonment rate. Within the EU, national governments have set specific goals for geothermal deployment, therefore, policy makers may find it important to improve the success rate of initiated geothermal projects by reducing early abandonment. Because this parameter does not quantify the positive impact of the policy measures in monetary terms, a benefit cost ratio is considered as a second policy performance indicator. This indicator is a ratio of the additional private net benefit to the cost of the policy instrument. A third policy performance indicator focusses on the reduction in investment risk. This indicator calculates at what cost different policy instruments reduce the probability that a continued geothermal project results in an economic loss. The policy target is then to reduce this investment risk to a minimum at least costs. Policy measures can also result in unwanted side-effects. One such side-effect is the occurrence of windfall profits, which is analyzed last. The results of the analyses are presented graphically; the exact data of the results are presented in Tables 5-7 of Annex B. Note that in all cases, there are no major changes in the selected development scenarios. The binary power plant is never selected, and most active projects produce heat for both high and low temperature applications.

Performance indicator I: reduction in abandonment rate

We first evaluate how each policy measure affects the abandonment rate. If the policy measure should aim for increasing the size of the sector and the amount of installed geothermal capacity, then the policy instrument should aim to decrease the rate at which a geothermal energy project is abandoned at an early stage. We search for the level of support that is needed to reduce the probability of abandonment after the first drilling to 40%, 30%, 25% and 20%. The acceptable error is 1%. Without policy support, the abandonment rate is 45%. The upper pane of Figure 5 shows the cost effectiveness for the single policy instruments and their different levels. The horizontal axis shows the reduction in abandonment rate as the positive effect of the policy measure and the vertical axis represents the associated public cost to reach the effect.

To reduce the abandonment rate of 45% to 40%, a heat premium of 2.35 €/MWh is the most cost-effective policy instrument because similar impacts can be reached at the lowest cost. Also, a tax rebate of 84% and a recoverable loan of 22% could be implemented to reach an abandonment rate of 40%. However, in that case the public cost would be higher compared to the heat premium measure. The heat premium is a policy instrument which technically has no limit. The higher the heat premium, the more the abandonment rate is reduced. The relation between the abandonment rate and the public cost appears to be non-linear: the additional public cost gradually increases for each extra percent point drop in abandonment rate. The level of the recoverable loan and the tax rebate are limited to 100%. Hence, with a recoverable loan the abandonment rate cannot be further reduced than 25%, and a tax rebate of 100% results in an abandonment rate of 39.5%. Different from the other policy instruments, the insurance system *increases* the abandonment rate. The underlying explanation is that the firm can recover investment costs after abandonment.

Because public support is often provided through a combination of policy instruments, we also analyse a set of combined policy measures. The lower pane of Figure 5 presents the results for combining the policy measures that individually lead to an abandonment rate of 40%. Combining policy instruments does not lead to further reductions in abandonment rate. If the single objective of the government is to reduce the abandonment rate, the heat premium should be adopted as the single policy instrument.

Policy instruments for geothermal energy deployment are not only implemented to reduce project abandonment rates. They should also aim at increasing project profitability, reducing investment risk and avoiding unwanted side-effects such as the occurrence of windfall profits. By analysing these performance indicators as well, we show that the preference for a heat premium is not that clear-cut.

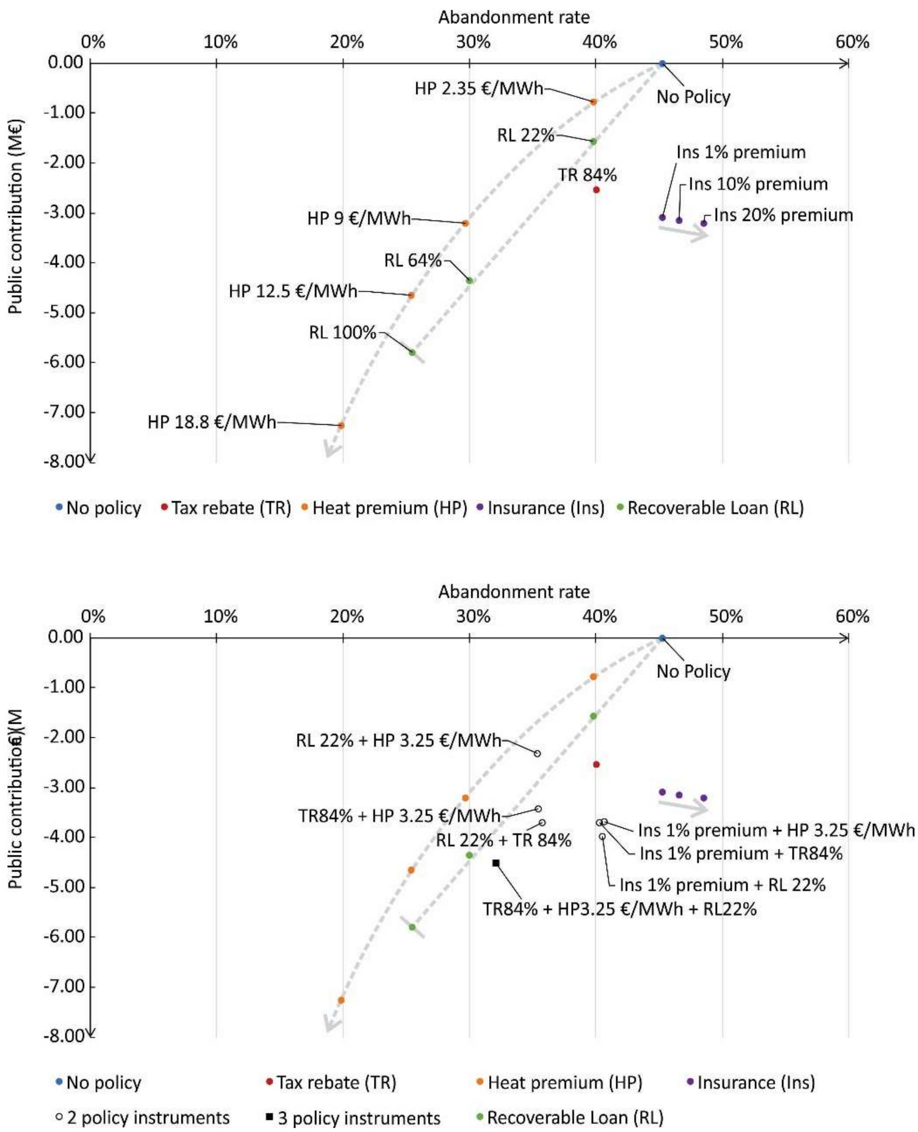


Figure 5. Impact of the different policy instruments on the probability that a geothermal project is abandoned after the first drilling. The upper pane presents the impact and the public contribution of the single policy instruments. In the lower pane, the combinations of policy measures that individually result in an abandonment rate of 40% are added. The public contribution is a cost and therefore results in a negative value.

Performance indicator II: benefit to cost ratio

To analyze whether the benefits of the policy instrument outweighs its cost, we calculate a benefit to cost ratio. The benefit to cost ratio is the added private project value per Euro of public contribution. This could be a policy goal, for example when the government would expect that firms would invest the added value to make the geothermal sector grow further. We analyse how much private value is created additionally to the expected private value in the base case for each Euro spend by the government. Note that a ratio smaller than 1 does not imply that the policy instrument should not be adopted. In this analysis, only the private net revenues are considered, the environmental net benefit of geothermal energy deployment is not included. The grey line in Figure 6 shows the points at which the additional added value equals the public cost. This is the case for the recoverable loan of 22%, the tax rebate of 84% and the insurance system with 1% insurance premium. Points at the left of (below) this line show that the ratio of added private value to public cost is smaller than one, meaning a lower cost efficiency of the policy measure. This includes all insurance systems that apply a premium larger than 1%, because of the higher premium that needs to be paid by the firms and the additional costs to the government. The public cost increases because a higher premium level results in a higher probability that a geothermal project is abandoned. The cost efficiency of the recoverable loan decreases as the policy support level increases. If more than 22% of the loan is paid by the government, the cost efficiency is lower than one. To the right and above the grey line, the more cost-efficient policy measures are found. Only the heat premium appears here: for each euro spend by the government, the added private value is about 2 €, regardless of the height of the premium.

We observe that all the combined policy measures are in general a favourable way for cost-efficiently increasing the additional private value. This is most evident from combining tax rebate, relative loan, and insurance premium. The combination of these measures is always more cost-effective than increasing the level of a single measure. This is less straightforward for combinations that involve the heat premium, which never reach the cost-efficiency level of heat premium as a single measure.

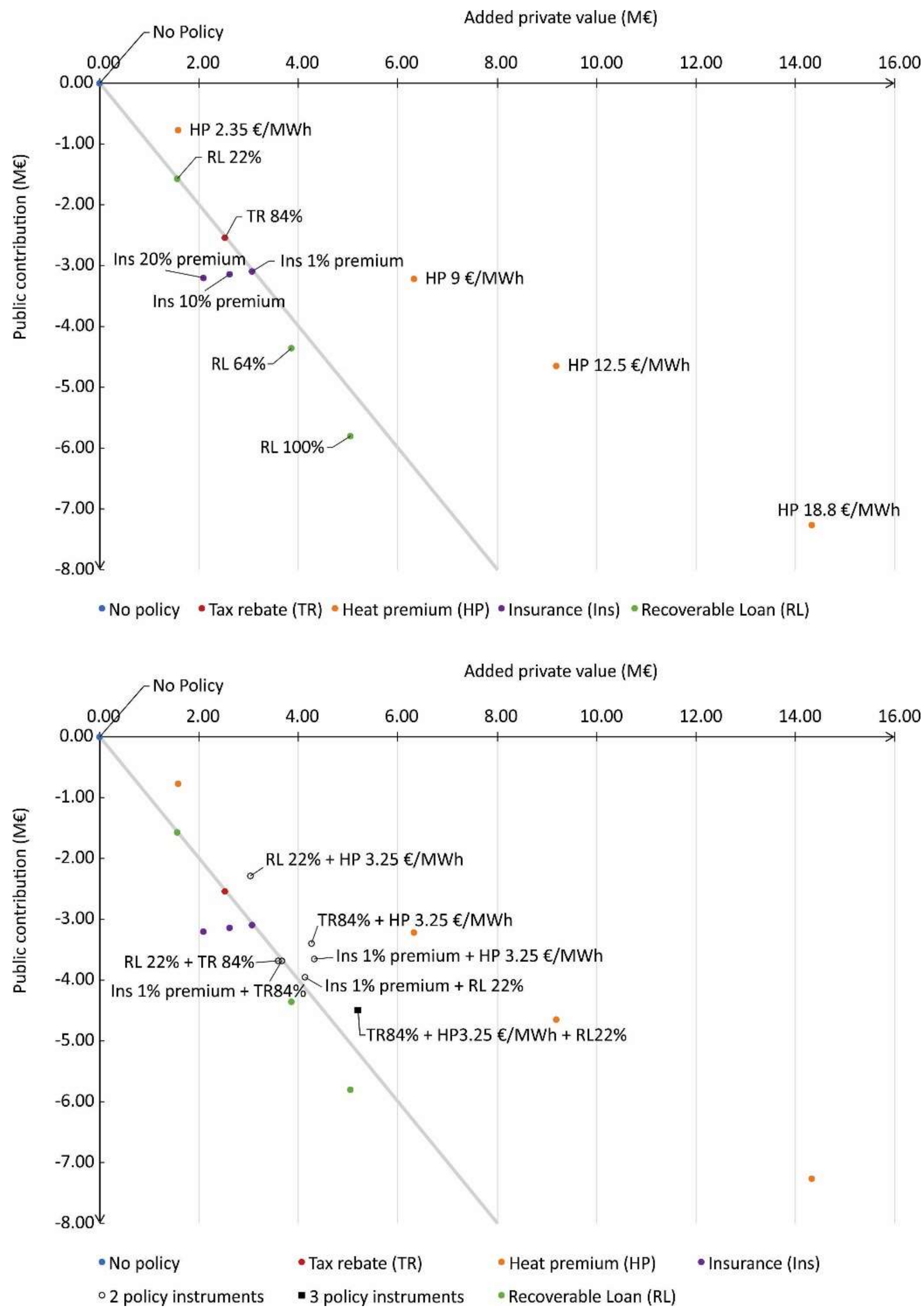


Figure 6. The impact of the different policy instruments on the added private value and the corresponding public contribution.

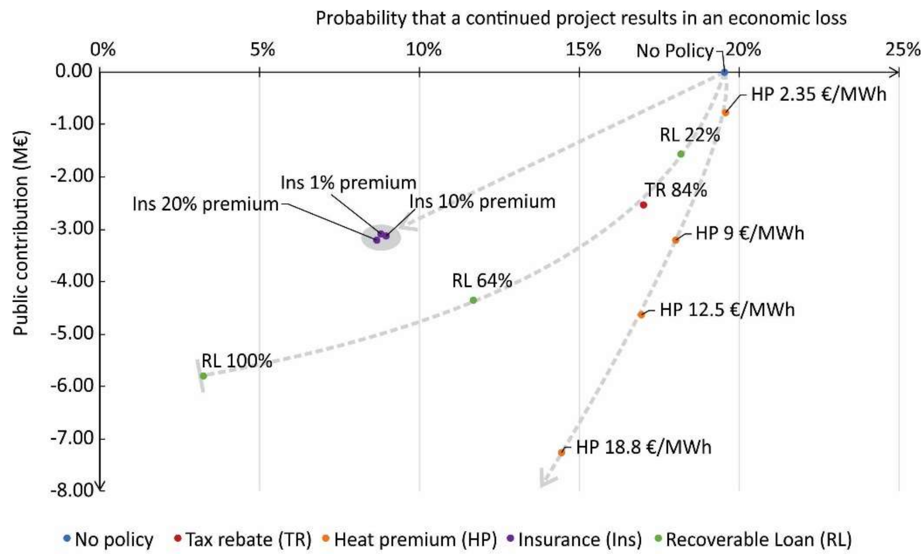
Performance indicator III: to reduce financial risk

To evaluate each policy instrument for its impact on financial risk mitigation, we analyse the probability that with the policy instrument in place, a continued project still results in a negative NPV. The upper pane of Figure 7 shows that although the insurance premium is not effective in decreasing the abandonment rate, it reduces the probability that a continued project results in an economic loss. Note that whereas the level of premium to be paid affects the abandonment rate, the premium level does not have an impact on the probability that a continued project results in an economic loss. The reason is that at abandonment, the insurance premium makes up a larger part of the calculated NPV compared to the cases where the project goes to further development. This means that in their decision to adopt the insurance system, the government should be aware that the financial risk level will not be affected by setting a higher premium. Higher premium levels will rather result in larger abandonment rates, with consequently higher public costs. Note that we do not assess the economic feasibility of setting-up an insurance system where the revenues from the premiums have to cover the refunds.

Similarly, the recoverable loan reduces the probability that a continued project results in an economic loss. It can reduce this probability up to 3.3% if the government is willing to pay for the total investment cost if the project turns out unprofitable. It is therefore a potentially stronger policy measure than the insurance premium but comes at a higher public cost than the insurance system. The insurance system only refunds the drilling costs, whereas the recoverable loan refunds *all* the investment costs partly or completely, depending on the support level and the project's feasibility.

The heat premium also reduces the number of projects ending with a negative NPV, but it is not very effective: to reduce the risk of unprofitable geothermal developments, the public cost would be much higher than when a recoverable loan would be applied. The reason for this is that only developed projects benefit from a heat premium, and that among those, the support mainly goes to the already profitable projects due to the mechanisms that result in windfall profits which will be discussed in the next subsection.

The tax rebate of 84% reduces the financial risk to 17%. Hence, whereas a heat premium of 2.35 €/MWh, a recoverable loan of 22%, and a tax rebate of 84% result in the same rate of abandonment (40%), theses policy measures clearly have a different impact on the financial risk. Compared to the heat premium, the higher cost of the tax rebate and the recoverable loan could be justified by the additional reduction in financial risk that these policy instruments provide. Different from the other results, combining policy measures can result in increased cost efficiency. When the insurance system is combined with the recoverable loan, there is a clear shift to left. The combination of these policy instruments results in an increased reduction of the financial risk compared to the case where these policy measures are adopted as single policy instruments. Combining the heat premium with the insurance system can also result in increased cost efficiency. This increased effectiveness could justify the additional public cost that result from these combinations.



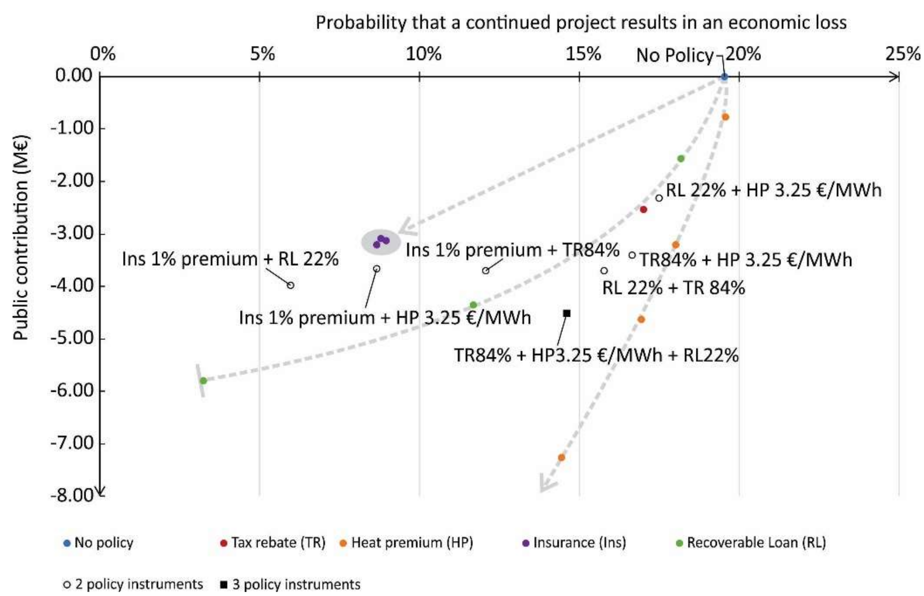


Figure 7. Impact of the different policy instruments on the probability that a continued project results in an economic loss and the corresponding public contribution.

Performance indicator IV: to avoid the occurrence of windfall profits

Besides the ability of policy instruments to deliver investment, also the occurrence of windfall gains need to be assessed (Gross et al., 2010). To analyse whether certain policy instruments provide unnecessary financial support to geothermal energy projects, we compare the box plots for the different policy instruments applied with the box plot of the base case with regards to how the upper whisker of the box plots changes compared to the base case scenario. Figure 8 shows that when the heat premium is applied, the box plot is much more skewed: the box and whiskers are uneven at either side of the modus. The distribution is positively skewed, with a more pronounced tail at the upper side. Compared to the base case, the lower quartile stays the same, the upper quartile is increased, the upper whiskers are longer and the upper outliers are higher values. Such skewness indicates the occurrence of windfall profits, especially since it is apparent that projects at the lower quartile do not benefit from the additional revenue received. This results from the underlying mechanics of a heat premium, which is only received by projects that go to the development phase, and to an increasing degree to more successful projects that produce more heat. Projects that are abandoned and hence are situated among the lower quartile do not receive this financial support.

When a tax rebate is applied, the median increases because investment costs are reduced. This policy measure does not result in major changes compared to the base case scenario: the upper whisker is the same in the length and hence, there is no sign of windfall profits.

A recoverable loan does not cause windfall profits, which is evident from the position of the upper quartile and the extreme values, compared to the base case. The effect is however evident for the lower whisker. The higher the level of the recoverable loan, the higher up the lower whisker is being pushed, resulting in less projects ending with an economic loss. So instead of creating windfall profits, this policy instrument clearly targets projects that require policy support the most.

When an insurance system is applied, there is also no indication of windfall profits. However, note that the upper quartile is a little bit lower compared to the base case scenario and that now also at the lower end of the box plot outliers appear. This indicates that the distribution is tightened, with both the upper and lower tails becoming thinner making also the lower outliers visible in Figure 8. In other words, there is less probability on higher profits and losses with insurance than without policy measures, and more projects end up around the median. Looking at how the insurance system works to explain these findings, the insurance can intervene at two moments. In case of a project that is abandoned, 90% of the first drilling is paid back and therefore a large part of the initial investment cost is covered. Obviously, this has a significant positive effect on those projects that can be find in the lower part of the distribution, since private losses are limited to 1.8-2.8 M€ depending on the level of the premium. When a developed project results in an economic loss, the second drilling is paid back for 90%, but this reduction covers a relatively smaller share of the total investment costs and hence, the impact is much smaller than in case of an abandoned project. More risky and loss-making projects are abandoned sooner, therefore less projects that are developed, turn out to be unprofitable. The insurance premium comes at an extra cost for any project, also the successful ones that do not get any refund Consequently, no windfall profits can be generated from this system. This by itself does not explain the thinning of the upper tail of the distribution. The primary cause of this is the influence the insurance premium has on the project decisions, and especially the final investment decision. Because a significant part of the otherwise sunken investment costs can be recovered, the option to abandon a project becomes more attractive. As a result, and as was mentioned earlier, projects with some risk on ending up with a negative NPV will be abandoned rather than developed, which shows as a shrunken inter-quantile distance.

If either the insurance or the recoverable loan is combined with a heat premium, there is a sign of windfall profit. The upper whisker is increased compared to the application of the insurance and the recoverable loan as single policy instruments. In case the insurance is combined with the recoverable loan, there is no occurrence of windfall profits. This is in line with the expectations resulting from how the individual measures work.

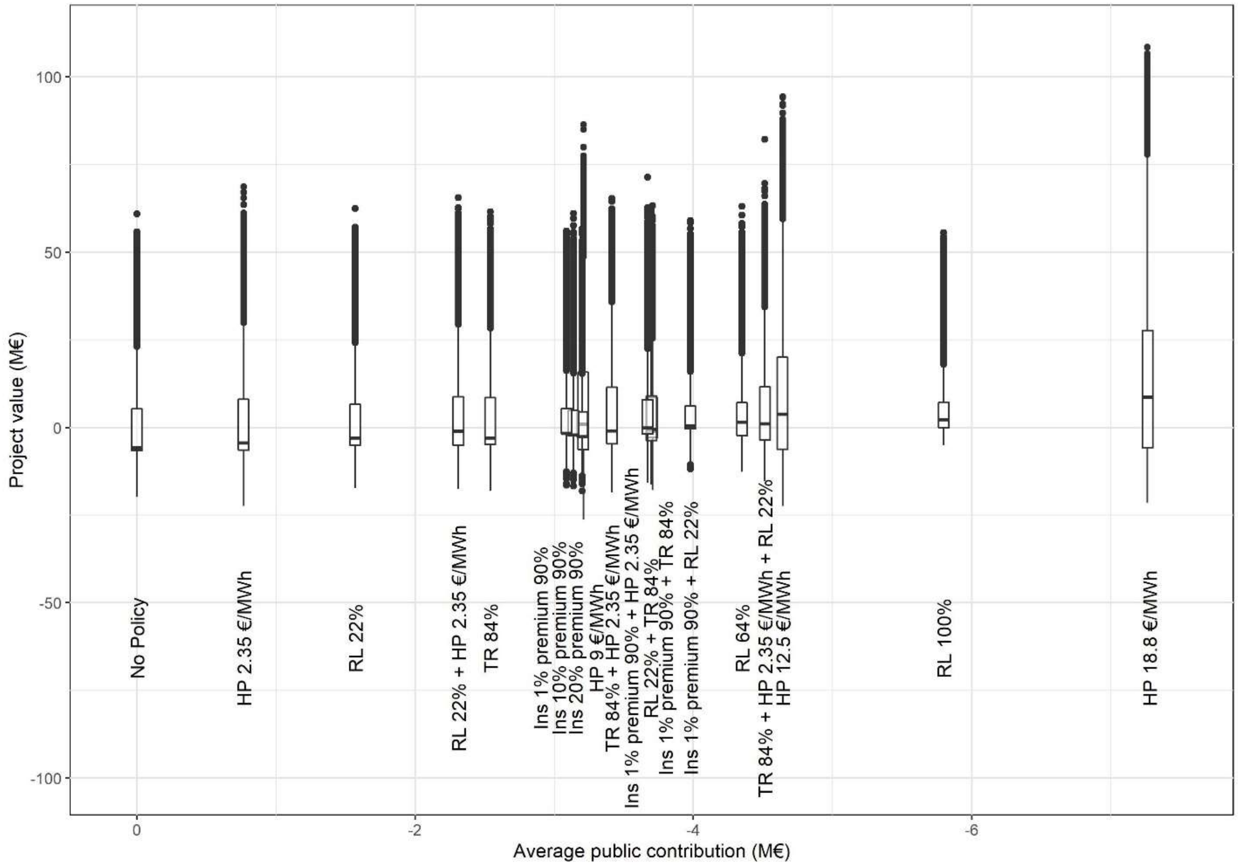


Figure 8. Box plot diagrams of the project values for the single and combined policy instruments, ranked according to their associated public cost. If the upper whiskers are longer compared to the No Policy case, windfall profits occur.

Summarising over the results of all objectives to stimulate deep geothermal uptake, we can argue that the preferred policy measure strongly depends on the target set. This is in line with other studies that analyse the impact of different policy instruments on investment strategies (see e.g. Kangas *et al.* (2011)). To draw conclusions on the cost efficiency of different policy instruments, we analysed their impact from four different viewpoints: the probability on project abandonment, on the occurrence of windfall profits, on the probability that a continued project still results in an economic loss, and on the added private value. These four aspects can all be part of policy objectives, and due to counteractions and non-linearity the selection is not always as straight forward as may appear at first sight. Table 4 provides a summary of the policy instruments and their effectiveness towards different policy objectives.

Policy instrument *Policy level*	No policy 0	Recoverable Loan 22– 100%	Heat Premium 2 – 13 €/MWh	Tax Rebate 84 – 100%	Insurance premium 1%/10%/20%
Support method/type of support?	/	Cost and risk sharing during exploration and development	Subsidize produced heat	Investment cost reduction	To cover losses in case of project abandonment
Abandonment rate	45%	25.5% - 39.8%	24.5% - 39.9%	39.5% - 40.1%	45% - 49%
Added private value (€) per Euro public contribution	0	0.9 - 1	~2	1	0.5 - 1
Probability of unprofitable geothermal development	19.55%	3.3 – 18.2%	16.9-19.6%	16.4-17%	8.7-8.8%
Occurrence of windfall profits	No	No	Yes	No	No
General policy impact	/	More projects developed,	More projects developed and	Limited	Reduced investment risk

		Reduced investment risk, no windfall profits	added private value		
Side effects	/	loss of money	Windfall profits	Limited	Less projects developed and loss of money

Table 4. Summary of the effectiveness of the different policy instruments that are analysed, demonstrated quantitatively for the policy relevant parameters (abandonment rate, added private value, project profitability, windfall profits), and discussed qualitatively summarizing strong and adverse effects.

The selection of the preferred instrument depends on the policy targets set and the importance policy makers attach to each of these targets. If only the reduction in abandonment rate or the added private value would be considered, the heat premium would come forward as the most desirable policy instrument. In contrast to the tax rebate and the recoverable loan there is no actual limit to the level of the premium and larger reductions in abandonment rate could be targeted. An insurance scheme increases the abandonment rate.

Efficient policy measures are those where public support result strongly increase the project value. A heat premium will increase the private value of the geothermal energy project and it results in a higher cost efficiency compared to the tax rebate, the recoverable loan, and the insurance scheme. For the latter two, the increase in project value is actually lower than the public support to the projects.

If the policy objective is to avoid loss-making projects, a recoverable loan or an insurance scheme could both be implemented as these instruments are designed to target the investor's risk and increase the probability that a continued project turns out economically profitable. Reducing the investment costs by means of a tax rebate, is not efficient in decreasing investment risk. Also the heat premium does not target risk reduction.

A typical policy concern of support mechanisms is to avoid windfall profits. The heat premium is the only instrument that triggers windfall profits because it subsidizes energy production. Public funding therefore flows mainly to successful projects.

Everything considered, none of the policy instruments can satisfy the portfolio of policy targets. However, the recoverable loan comes forward as the preferred policy instrument to mobilize risk capital: it reduces the abandonment rate and the risk of loss-making projects and no windfall profits occur. This preference is not reflected in the countries that have policy measures in place to cover for the geothermal drilling and exploitation risks. These countries (e.g. Belgium, France, Germany, and the Netherlands) have instead adopted an insurance scheme, and also within the sector this is the policy support that is typically requested. While we have demonstrated that an insurance scheme is effective in improving the profitability of projects, a side effect is that also the abandonment rate significantly increases. This probably indicates that this adverse effect is insufficiently understood by both the policy makers and the geothermal sector.

The analyses of combined policy measures show that these can be, but not necessarily are, more cost efficient than single policy measures. However, this study only explored the potential of combining policy measures, and further work is needed to map out the different sweet spots. Also, we have attempted to approach policy from four distinct policy objectives. This has resulted in additional fundamental insight on which individual measures to prefer, but does not yet provide an answer to how combined policy objectives would best be realised.

5 Conclusions

Whereas the current state-of-the-art on deep geothermal energy deployment seems to be stuck in traditional NPV calculations to which a sensitivity analysis is added, we aim to advance the insights in risk mitigation by developing a geological economic model which simultaneously integrates geological, technical and market uncertainty, and which at the same time takes into account managerial flexibility. The model has been used to calculate investment risk and evaluate the impact of different policy measures that can be adopted on a national level to support the development of deep geothermal energy projects. We also compared their effectiveness to their public cost.

We integrate different types of uncertainty and include the flexibility to abandon the geothermal energy project after the first drilling. By including the possibility to abandon the project, we adopt a real options-style decision framework and take a more realistic approach to model the development of a geothermal project. Especially for this kind of high-uncertainty, high-capital-intensive projects, the results of this approach differ significantly from a standard NPV calculation and offer much deeper insights in the risks associated with deep geothermal energy development. It is, for example, possible to model project abandonment, to calculate the abandonment rate, and to determine causes and consequences. This approach allowed us to reach the following conclusions.

Looking into the geological parameters, we find that flow rate has more impact on the economic feasibility than reservoir temperature. This observation becomes clear from the probabilistic distribution of the reservoir parameters of activated projects, and from the average flow values of projects that are activated. This observation is supported by both literature and field experience.

Although different geothermal development scenarios can be selected, the geothermal energy project mostly results in a high heat temperature application and the binary power plant is never selected. Because of the low ORC efficiency, the amount of electricity produced from geothermal heat is low. Furthermore, also the high temperature heat production is limited which results in a revenue stream that is too low to cover operational costs. Even if a feed-in tariff would be applied, a binary power plant is never selected for the geological conditions considered (i.e. those similar to the Campine Basin) and the current level of technical development.

The choice of policy instrument depends on the policy target. Most countries adopt an insurance scheme to cover potential well failure and long term exploitation risks. However, based on our analysis, a recoverable loan is most preferred to mobilize risk capital as it reduces both the investment risk and the abandonment rate, and it avoids windfall profits. These results demonstrate the intricacies of choosing the correct policy measure and the need to support such policy decisions with quantitative analyses.

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8 Annex A: details of the geological economic model and the NPV calculation

COSTS

Investment costs

Phase 1: Exploration. The investment cost of the exploration phase includes a seismic survey, a borehole design, and a first drilling. This latter cost is not constant across the Monte Carlo analysis and depends on the value of the depth (in m) drawn from the distribution. Moreover, there exists a 30% chance the drilling cost is topped up with an additional stochastic cost with a normal distribution (mean: 1000 €/m, standard deviation: 200).The first phase investment cost equals (excluding the drilling risk cost):

$$I_E = \frac{-500\,000\,€}{(1+r)^2} - \frac{500\,000\,€}{(1+r)^2} - \frac{Depth * 1\,500\,\frac{€}{m}}{(1+r)^3}$$

If the project is abandoned after the first drilling, the NPV of the project is I_E.

Phase 2: Development. If the project is continued after the first drilling, the second drilling takes place and either a heat plant or a power plant is installed. The investment cost of the second drilling equals:

$$I_D = \frac{-Depth * 1\,500 \frac{€}{m}}{(1+r)^4}$$

The investment cost of the heat plant is assumed constant and equals I_{HP} = 1 110 000 Euro. We consider cascaded use of energy. When the geothermal energy project is further developed for electricity production, both an electricity plant and a heat plant are installed. The investment cost of such a binary power plant is based on (Walraven et al., 2015a) and the cost per unit of electrical energy output decreases with increasing capacity with a minimum of 3000 €/Q_{el}:

$$I_{pp} = \frac{-I_{HP} - Max[3000Q_{el}\,; (13\,000 - \;60Q_{el})Q_{el}]}{(1+r)^5}$$

Annual costs

Annual costs include operational costs (OC) which occur after drilling, from year 5 until year 40. Annual operational costs equal 6% of total investment costs of the drillings and power plant.

ENERGY PRODUCTION

The energy produced by the geothermal energy system is stochastic and depends on the temperature and flow drawn from the distributions. Three scenarios (i = 1,2,3) can occur, with three possible energy outputs, k=LT, HT, El.

Scenario 1, the geothermal project is developed into a LT application.

In case the extracted heat is used in a plant that only produces heat for low temperature applications (T>35°C), the annual heat production is then:

$$Q_{1,LT} = \frac{Calculated\ flow \frac{m^3}{h} * \frac{1000kg}{m^3} * \frac{4.19kJ}{kg} * (T - 55°C) * 8760h}{3600kJ * 1000},$$

$$Q_{1,HT} = Q_{1,El} = 0.$$

Scenario 2, the geothermal project is developed into a HT application.

In case the extracted heat is used in a plant that produces heat for both HT and LT applications (T>90°C), annual heat production for the low temperature application is then:

$$Q_{2,LT} = \frac{Calculated\ flow \frac{m^3}{h} * \frac{1000kg}{m^3} * \frac{4.19kJ}{kg} * 35°C * 8760h}{3600kJ * 1000}.$$

The annual heat production for the high temperature application equals:

$$Q_{2,HT} = \frac{Calculated\ flow \frac{m^3}{h} * \frac{1000kg}{m^3} * \frac{4.19kJ}{kg} * (T - 90°C) * 8760h}{3600kJ * 1000},$$

$$Q_{2,El} = 0.$$

Scenario 3, the geothermal project is developed for electricity and heat production.

In case the extracted heat is used in a plant for low and high temperature application combined with energy production (T>110°C), annual heat production for the low temperature application is then:

$$Q_{3,LT} = \frac{Calculated\ flow \frac{m^3}{h} * \frac{1000kg}{m^3} * \frac{4.19kJ}{kg} * 35°C * 8760h}{3600kJ * 1000}.$$

Annual heat production for the high temperature application:

$$Q_{3,HT} = \frac{Calculated\ flow \frac{m^3}{h} * \frac{1000kg}{m^3} * \frac{4.19kJ}{kg} * 20°C * 8760h}{3600kJ * 1000}.$$

Electricity is produced by an ORC with an efficiency of 11% and an availability of 90%. Annual heat production equals:

$$Q_{3,El} = \frac{Calculated\ flow \frac{m^3}{h} * \frac{1000kg}{m^3} * \frac{4.19kJ}{kg} * (T - 110°C) * 8760h * 0.11 * 0.9}{3600kJ * 1000}.$$

NPV calculation without governmental intervention

For each scenario, the NPV is calculated and the scenario with the highest NPV is selected:

$$NPV = Max(NPV_1; NPV_2; NPV_3; I_E)$$

In case the project is abandoned after the first stage surveys, then the value of the project equals:

$$NPV_E = I_E.$$

In case the project is continued after the first stage, three NPV scenarios (i) can occur. Total investment cost for the LT application or HT/LT application is:

$$I_{1,2} = I_E + I_D + I_{HP}$$

The total investment cost for the binary power plant is:

$$I_3 = I_E + I_D + I_{PP}$$

To pay for these investment costs, the firm pays an annual principal (PPMT) and interest payment (IPMT) for a loan based on an interest rate of 7%. The payment schedule is constant and after 20 years the loan is payed back. The energy prices are stochastic and follow the price process presented in Table 2. The lifetime of the geothermal energy system is 35 years. The value of the project equals:

$$NPV_i = \sum_{t=5}^{40} \frac{\sum_k Q_{i,k} * p_{t,k} - OC}{(1+r)^t} - \sum_{t=5}^{25} \frac{PPMT + IPMT}{(1+r)^t},$$

NPV calculation given a recoverable loan (RL) of X%

If a recoverable loan of $X \in [0,1]$ is applied, the firm pays (1-X) of the investment cost and the government pays X of the investment cost. If from year 5 until year 25 the present value of the net cash flow is smaller than 0, the government will not recover part of its contribution and the recovered part in year t (RP_t) is 0. If the present value of the cash flow is larger than 0, the government can recover its contribution or at least part of it.

The present value of the net cash flow (NCF) in year t then equals:

$$NCF_{RA,t} = \frac{\sum_k Q_{i,k} * p_k - OC}{(1+r)^t} - (1-X) * \frac{PPMT + IPMT}{(1+r)^t} - RP_t,$$

The present value of the governmental contribution (GC) in year t then equals

$$GC_{RA,t} = X * \frac{PPMT + IPMT}{(1+r)^t} - RP_t.$$

With the present value of the recovered part in year t:

$$RP_t = MIN\left[X * \frac{PPMT + IPMT}{(1+r)^t}; \frac{\sum_k Q_{i,k} * p_k - OC}{(1+r)^t} - (1-X) * \frac{PPMT + IPMT}{(1+r)^t}\right] \; for\; NCF_{RA,t} > 0\,.$$

NPV calculation given a federal tax rebate of X%

A federal tax rebate results in a reduced investment cost for the firm. The tax rebate is not applicable to the seismic survey. With a tax rebate of X%, the investment cost for the first phase equals:

$$I_E = \frac{-500\,000\,€}{(1+r)^2} - (1-X) * 0.3399\left[-\frac{500\,000\,€}{(1+r)^2} - \frac{Depth * 1\,500\frac{€}{m}}{(1+r)^3}\right].$$

The investment cost for the LT application and the HT/LT application (scenario 1 and 2) equals:

$$I_{1,2} = \frac{-500\,000\,€}{(1+r)^2} - (1-X) * 0.3399\left[-\frac{500\,000\,€}{(1+r)^2} - \frac{Depth * 1\,500\frac{€}{m}}{(1+r)^3} + I_D + I_{HP}\right].$$

The investment cost for the application where electricity production is combined with a HT/LT application (scenario 3), the investment cost equals:

$$I_3 = \frac{-500\,000\,€}{(1+r)^2} - (1-X) * 0.3399\left[-\frac{500\,000\,€}{(1+r)^2} - \frac{Depth * 1\,500\frac{€}{m}}{(1+r)^3} + I_D + I_{PP}\right].$$

For the calculation of the NPV, this reduced investment cost will result in a reduced loan and hence reduced principal and interest payments.

The governmental contribution for each scenario then equals

$$GC_{TR,E} = X * 0.3399 \left[-\frac{500\,000\text{ €}}{(1+r)^2} - \frac{Depth * 1\,500 \frac{\text{€}}{m}}{(1+r)^3} \right],$$

$$GC_{TR;1,2} = X * 0.3399 \left[-\frac{500\,000\text{ €}}{(1+r)^2} - \frac{Depth * 1\,500 \frac{\text{€}}{m}}{(1+r)^3} + I_D + I_{HP} \right],$$

$$GC_{TR,3} = X * 0.3399 \left[-\frac{500\,000\text{ €}}{(1+r)^2} - \frac{Depth * 1\,500 \frac{\text{€}}{m}}{(1+r)^3} + I_D + I_{PP} \right].$$

NPV calculation given a heat premium (euro/MWh_{th})

If the government gives a heat premium (HP) for each MWh_{th} produced, the NPV equals

$$NPV_i = \sum_{t=5}^{40} \frac{\sum_k Q_{i,k} * p_k - OC}{(1+r)^t} - \sum_{t=5}^{25} \frac{PPMT + IPMT}{(1+r)^t} + \sum_{t=5}^{40} \frac{\left(Q_{i,LT} + Q_{i,HT}\right) * HP}{(1+r)^t},$$

and the governmental contribution equals

$$GC_{HP,i} = \sum_{t=5}^{40} \frac{\left(Q_{i,LT} + Q_{i,HT}\right) * HP}{(1+r)^t}.$$

Note that a heat premium is not applied in the first phase. Only projects that enter the second development phase benefit from this policy instrument.

NPV calculation given an insurance of 90% on the first or second drilling

The public insurance covers the drilling cost in case the project turns out economically unfeasible. We ran 3 scenarios considering a premium of 1%, 10%, and 20%. If the project is abandoned in the first phase, the insurance cost is only paid for the first drilling. If the project is continued, the insurance is paid again a second time, for the second drilling. The insurance cost to the private firm is equal to:

$$Ins = premium * \frac{-Depth * 1\,500 \frac{\text{€}}{m}}{(1+r)^t}.$$

For each scenario: if the calculated NPV is negative, the NPV is recalculated, taking into account a refund of 90% of the drilling cost, and the scenario with the highest NPV is selected. In case a refund is needed, the governmental contribution equals:

$$GC_{Ins} = 0.9 * \frac{-Depth * 1\,500 \frac{\text{€}}{m}}{(1+r)^t}.$$

9 Annex B: model results for the different individual policy instruments and combined policy instruments

	Recoverable loan 21.63%			**Heat premium 2.35 €/MWh**			**Tax rebate 84%**		
	Probability	Private NPV	Public contribution	Probability	Private NPV	Public contribution	Probability	Private NPV	Public contribution
(1) Abandon	39.83%	-5,052,419 €	-1,394,460 €	39.85%	-6,446,233 €	0 €	40.07%	-4,744,016 €	-1,642,114 €
(2) LT Heat	0.13%	-3,901,629 €	-2,852,476 €	0.14%	-6,058,188 €	-1,978,515 €	0.13%	-4,037,783 €	-3,155,873 €
NPV<0[1]	0.11%			0.13%			0.10%		
NPV>0	0.02%			0.01%			0.03%		
(3) HT Heat	60.04%	7,279,563 €	-1,680,229 €	60.00%	8,226,165 €	-1,274,470 €	59.80%	8,725,115 €	-3,140,196 €
NPV<0[2]	18.18%			19.60%			17.01%		
NPV>0	41.86%			40.41%			42.79%		
(4) Power plant	0.00%	0 €	0 €	0.00%	0 €	0 €	0.00%	0 €	0 €
Project value		2,352,975 €	-1,567,954 €		2,358,351 €	-767,582 €		3,310,904 €	-2,539,875 €
Added value per 1€ public cost	1			2.06			1		

	Recoverable loan 64%			**Heat premium 9 €/MWh**		
	Probability	Private NPV	Public contribution	Probability	Private NPV	Public contribution
(1) Abandon	30.00%	-2,322,099 €	-4,128,176 €	29.72%	-6,449,828 €	0 €
(2) LT Heat	0.26%	-1,080,891 €	-8,128,131 €	0.36%	-4,199,925 €	-6,383,521 €
NPV<0	0.18%			0.29%		
NPV>0	0.08%			0.07%		
(3) HT Heat	69.74%	7,665,372 €	-4,429,916 €	69.92%	12,928,040 €	-4,557,302 €
NPV<0	11.68%			18.03%		
NPV>0	58.06%			51.90%		
(4) Power plant	0.00%	0 €	0 €	0.00%	0 €	0 €
Project value		4,646,415 €	-4,349,089 €		7,108,052 €	-3,209,629 €
Added value per 1€ public cost	0.89			1.97		

	Recoverable loan 100%			**Heat premium 12.55 €/MWh**		
	Probability	Private NPV	Public contribution	Probability	Private NPV	Public contribution
(1) Abandon	25.50%	0 €	-6,446,930 €	25.41%	-6,443,975 €	0 €
(2) LT Heat	0.38%	754,286 €	-11,365,106 €	0.52%	-2,937,088 €	-8,376,885 €
NPV<0	0.09%			0.38%		
NPV>0	0.29%			0.14%		
(3) HT Heat	74.11%	7,860,997 €	-5,547,276 €	74.07%	15,696,733 €	-6,205,742 €
NPV<0	3.26%			16.94%		
NPV>0	70.86%			57.13%		
(4) Power plant	0.00%	0 €	0 €	0.00%	0 €	0 €
Project value		5,828,838 €	-5,799,064 €		9,973,953 €	-4,640,320 €
Added value per 1€ public cost	0.87			1.98		

Table 5. Overview of simulation results for different levels of a recoverable loan, a heat premium, and a tax rebate

[1] Probability that a geothermal project which is further developed as a LT project still results in a negative NPV, i.e. an economic loss

2 Probability that a geothermal project which is further developed as a HT/LT project still results in a negative NPV, i.e. an economic loss

	Insurance 90% on 2nd drilling | 1% premium		
	Probability	NPV private value	Public contribution
(1) Abandon project	45.27%	-1,778,264 €	-4,730,793 €
(2) LT Heat	1.43%	-130,778 €	-4,043,634 €
NPV<0	0.64%		
NPV>0	0.79%		
(3) HT Heat	53.31%	8,730,590 €	-1,667,272 €
NPV<0	8.81%		
NPV>0	44.50%		
(4) Binary power plant	0.00%	0 €	0 €
Project value		3,847,112 €	-3,087,940 €
Added value per 1€ public cost	0.99		
	Insurance 90% on 2nd drilling | 10% premium		
	Probability	NPV private value	Public contribution
(1) Abandon project	46.60%	-2,271,571 €	-4,725,283 €
(2) LT Heat	1.20%	-27,665 €	-3,856,497 €
NPV<0	0.49%		
NPV>0	0.71%		
(3) HT Heat	52.21%	8,537,241 €	-1,705,308 €
NPV<0	8.96%		
NPV>0	43.24%		
(4) Binary power plant	0.00%	0 €	0 €
Project value		3,398,115 €	-3,138,284 €
Added value per 1€ public cost	0.83		
	Insurance 90% on 2nd drilling | 20% premium		
	Probability	NPV private value	Public contribution
(1) Abandon project	48.58%	-2,821,918 €	-4,728,229 €
(2) LT Heat	0.98%	349,188 €	-3,775,302 €
NPV<0	0.35%		
NPV>0	0.63%		
(3) HT Heat	50.44%	8,421,059 €	-1,720,766 €
NPV<0	8.67%		
NPV>0	41.78%		
(4) Binary power plant	0.00%	0 €	0 €
Project value		2,880,439 €	-3,201,843 €
Added value per 1€ public cost	0.66		

Table 6. Overview of simulation results for different insurance coverage levels and insurance premiums

	Heat premium 2.35 €/MWh + Ins 90% 2nd drilling | 1% premium			**TR 84% + Ins 90% 2nd drilling | 1% premium**			**Recov. Loan 21.63% + Ins 90% 2nd drilling | 1% premium**		
	Probability	Priv. NPV	Public contr.	Probability	Private NPV	Public contr.	Probability	Private NPV	Public contr.
(1) Abandon	40.67%	-1,777,253 €	-4,724,979 €	40.29%	-2,740,163 €	-3,669,518 €	40.50%	-370,565 €	-4,934,910 €
(2) LT Heat	2.40%	95,054 €	-6,066,439 €	0.20%	-2,598,475 €	-4,852,345 €	4.72%	979,291 €	-6,648,549 €
NPV<0	0.94%			0.15%			1.31%		
NPV>0	1.41%			0.05%			3.41%		
(3) HT Heat	56.93%	10,240,066 €	-2,815,229 €	59.51%	9,363,453 €	-3,724,907 €	54.78%	9,196,215 €	-3,039,320 €
NPV<0	8.69%			12.10%			5.98%		
NPV>0	48.27%			47.42%			48.80%		
(4) Power plant	0.00%	0 €	0 €	0.00%	0 €	0 €	0.00%	0 €	0 €
Project value		5,108,699 €	-3,670,056 €		4,463,218 €	-3,704,799 €		4,933,639 €	-3,977,428 €
Added value /1€ public cost	1.18			0.99			1.04		

	Recov. loan 21.63% + heat premium 2.35 €/MWh			**Recov. loan 21.63% + TR 84%**			**TR84% + heat premium 2.35 €/MWh**		
	Probability	Priv. NPV	Public contr.	Probability	Private NPV	Public contribution	Probability	Private NPV	Public contribution
(1) Abandon	35.40%	-5,052,389 €	-1,394,452 €	35.79%	-3,717,936 €	-2,668,284 €	35.49%	-4,743,104 €	-1,641,766 €
(2) LT Heat	0.19%	-3,523,108 €	-4,771,811 €	0.16%	-2,932,523 €	-5,343,339 €	0.19%	-3,186,106 €	-5,083,421 €
NPV<0	0.16%			0.13%			0.14%		
NPV>0	0.03%			0.03%			0.05%		
(3) HT Heat	64.42%	8,744,090 €	-2,806,478 €	64.05%	8,929,402 €	-4,269,047 €	64.32%	10,502,609 €	-4,387,699 €
NPV<0	17.51%			15.77%			16.67%		
NPV>0	46.90%			48.28%			47.65%		
(4) Power plant	0.00%	0 €	0 €	0.00%	0 €	0 €	0.00%	0 €	0 €
Project value		3,837,626 €	-2,310,372 €		4,384,431 €	-3,697,863 €		5,065,897 €	-3,414,489 €
Added value /1€ public cost	1.32			0.97			1.26		

	Reov. Loan 21.63% + TR84% + heat premium 2.35 €/MWh		
	Probability	Priv. NPV	Public contr.
(1) Abandon	32.13%	-3,717,887 €	-2,668,247 €
(2) LT Heat	0.30%	-1,818,054 €	-7,054,878 €
NPV<0	0.21%		
NPV>0	0.09%		
(3) HT Heat	67.57%	10,626,301 €	-5,379,557 €
NPV<0	14.61%		
NPV>0	52.97%		
(4) Power plant	0.00%	0 €	0 €
Project value		5,980,716 €	-4,513,460 €
Added value /1€ public cost	1.15		

Table 7. Overview of simulation results for different combinations of policy instruments that individually result in a 40% abandonment rate