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Research Article

# De-risking of geothermal prospect portfolios based on Value of Information and a play-based exploration approach: a case study for Slochteren reservoir development in the Netherlands[☆]

Marianne van Unen[a,*], Logan Brunner[a,1], Hans Veldkamp[a], Ruben Keijzer[b], Jan Diederik van Wees[a,b]

[a] TNO, Geoscience and Technology, Netherlands
[b] Utrecht University, Geosciences, Netherlands

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ABSTRACT

For the portfolio approach presented in this study, a Value of Information (VOI) methodology originally developed for oil and gas exploration has been adapted for geothermal exploration. A former VOI analysis for geothermal exploration uses a simple positive correlation associated with a fixed increase or decrease between follow up prospects, which does not take into account the spatial geological correlation between prospects. We introduce a methodological more advanced and robust VOI method, allowing the strength of geological correlation to vary with distance between prospects. The updated VOI analysis uses a decision tree approach, where the Net Present Value (NPV) of the first project takes the VOI for potential follow-up projects into account.

The updated portfolio approach was applied to a case study in the Netherlands to determine the benefits and added value of such approach for geothermal exploration. The results show that acquired information in the first prospects used for decisions in follow-up projects within the same geologic play contributes significantly to the business case and indicates that the development of the remaining prospects after the success of the first prospect is positive even with high initial risk. The expected uncertainty and anticipated spatial correlation in flow properties allows to effectively harness the VOI for a portfolio of prospects in such way that it increases the average profitability of the projects and lowers the risk. Geothermal areas that would mostly benefit from the improved VOI analysis are associated with large geological uncertainty and sufficient spatial geological correlation between prospects.

## 1. Introduction

The European Green Deal targets a renewable energy transition where geothermal energy has the potential to play an important role and is targeted to triple in the coming decade. Geothermal offers an excellent renewable energy source for heating and baseload electricity (Cordis, 2022; IOGP, 2024); it is local, constantly available, and independent of weather conditions. In many regions in Europe, relatively low enthalpy geothermal sources (ca. 40–150 °C) are being developed for district heating, marked by a significant potential and benefiting from a wealth of relevant data and reservoir characterization from past hydrocarbon exploration and production (EGEC, 2022). Additionally, skills from the oil and gas sector are applicable to the geothermal industry, including advanced drilling techniques, well production, and completion strategies, extensive knowledge in geoscience and formation evaluation, expertise in reservoir engineering, and the management of surface production facilities (IOGP, 2024). Rapid growth of geothermal development for district heating in the EU is imminent in various EU member states (EGEC, 2022). In the Netherlands, geothermal energy is a relatively young sector. The first successful geothermal drilling was in 2007 and the ambition is to increase the geothermal energy supply to cover 5 % of the country's heat demand by 2030 (which corresponds to 50 petajoules (PJ) of geothermal heat per year) (source: www.geothermie.nl). In the past 24 years geothermal exploration has been successful due

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* Corresponding author.
*E-mail address:* marianne.vanunen@tno.nl (M. van Unen).
[1] Present address: Urban Intelligence, Christchurch, New Zealand.

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to the abundance of subsurface oil and gas data, including thousands of (2 to 6 km deep) exploration and production wells, 2D and 3D seismic lines and hundreds of thousands of core plug measurements (source: www.nlog.nl). A 90 % success rate also demonstrates the current risk-averse investment mentality in geothermal, due to the low profit margins in comparison with oil and gas (Van Wees et al., 2020). In 2023, a total of 39 geothermal doublets at 27 locations were in place (saving more than 193 million $m^3$ of natural gas per year) associated with a total of 6.8 PJ of geothermal heat being produced in the Netherlands (source: www.geothermie.nl).

Currently, geothermal exploration and development for district heating is often focused on the development of a single asset, which for direct heating corresponds to a geothermal doublet system capable of producing heat for thousands of households. These systems consist of a producer and injector well for reservoir pressure support and avoidance of any release of produced brines at the surface (Van Wees et al., 2012). Due to the uncertainty in resource quality and associated investments required to reduce these uncertainties, systems have only been developed in areas with relatively low exploration risk. For direct heat exploitation, low-risk developments in mature oil and gas basins are possible when taking advantage of the wealth of existing subsurface data and model interpretations, such as demonstrated in the Netherlands (Wong et al., 2007; Van Wees et al., 2017; Mijnlieff, 2020). Unlocking higher risk areas can be promoted by a play-based portfolio approach, which is commonly used in the oil and gas industry (Coopersmith and Cunningham, 2002; Bratvold et al., 2007). In such an approach the experience and information obtained from one prospect (or many analogous) will be used optimally for de-risking of subsequent prospects within the same play i.e. Value of Information (VOI). If VOI is not being used, each new project will be equally risky. The learning effect of these single doublets is mostly local and sub-optimal for large areas and long-term evaluation, and hamper developments beyond the low-risk areas. The term play refers to a combination of unique geophysical, geologic, structural and/or stratigraphic elements that have resulted in a geothermal resource (Moeck, 2014). If these elements are shared and/or correlated in the areas of the portfolio, this may prove the presence of elements at a first prospect, reducing costs and risks for subsequent prospects, and thereby increasing the attractiveness of the play for market development. To assess the merits of a play-based approach, the trade-off between higher risk and reward based on VOI for follow-up prospects needs to be quantitatively evaluated in the face of uncertain outcomes and needs to include exit options. To this end, decision and event trees have proven a key methodology to optimize decisions under uncertainty (Begg et al., 2002). They have also been introduced, mostly for single assets, in geothermal exploration studies (Frick et al., 2010; Batini and Van Wees, 2011; Trainor-Guitton et al., 2014; Van Wees et al., 2014), and recently for prospect-portfolios in geothermal energy development in the Netherlands (Van Wees et al., 2020). They showed that a play-based approach and VOI can indeed facilitate de-risking and enhance market attractiveness, to unlock geothermal energy. In their study they adopted simplified and synthetic assumptions on Probability of Success (POS) and VOI for portfolio decisions and event trees. Furthermore, techno-economic evaluations were based on synthetic Net Present Value (NPV) values for successful or failed outcomes, and they used a suboptimal approach for exercising exit options.

The former VOI method of Van Wees et al., 2020 uses a simple positive correlation. When the prospect outcome is successful, the POS of follow-up prospects is increased by a fixed value, and when a prospect fails the POS of follow-up prospects is lowered by a fixed value. However, in this paper we introduce an improved method for portfolio analysis. This method is mathematically more advanced and robust, which allows to honour the spatial correlation strength when estimating the POS of follow up projects. The method considers the effect of imperfect information where correlation strength of a particular geological factor is expected as an exponential function of pairwise distance between prospects. The updated method preserves marginal probabilities and acknowledges that POS is affected by various geological factors influencing the NPV expectation curve. Finally, the application of exit options and pruning of the tree is performed automatically under the right conditions.

The improved method is subsequently applied to a realistic case study with actual property data for the central part of The Netherlands (Flevoland region). The Flevoland region is considered an unexplored area with limited wells and seismic data (Fig. 1). The target aquifer is the Rotliegend Slochteren Formation (Pluymaekers et al., 2012; Bouroullec et al., 2019). This aquifer has mainly been explored in the northern and northwestern parts of the country where the reservoir quality is good. Geothermal doublet systems exist in the northeastern part of the Flevoland region only. Whether the geothermal potential of the Rotliegend in the Flevoland area is high remains uncertain due to the uncertainty in the reservoir quality. Consequently, as a first step, a reservoir characterization study has been performed, in which property maps were generated based on various geological assumptions associated with burial anomaly, and porosity-depth and porosity-permeability relationships (Veldkamp et al., 2022). Probabilities were assigned to these maps, from which geothermal potential maps could be generated. Based on the updated subsurface property maps, heat demand and spatial limitations, five locations were selected in SW-, W- and NW-Flevoland for the determination of the probability of success of geothermal doublet systems at these locations in a single asset development perspective.

The business case and VOI of these five targeted locations were evaluated through a play-based portfolio approach. For the location selection and the VOI analysis, existing property maps from Veldkamp et al., 2022 were used. A priori-NPV calculations were made with a cost-engineering model, which is based on a choice in values of various operational parameters. These include parameters such as Capital Expenditure (CAPEX), Operational Expenditure (OPEX), power, load hours, Coefficient of Performance (COP), yearly net and gross revenue, tax and abandonment costs. It must be noted that the values of the input parameters are practical numbers based on Dutch experience and serve only as indicative values. For the VOI analysis, each portfolio location includes 5 doublet prospects that are developed consecutively. Here, each subsequent prospect uses the information of the previous prospect, which depends strongly on the correlation strength (k-value). For each location we compared two scenarios to highlight the sensitivity of the correlation strength. Power expectation curves (i.e. pre- and post-drill expectation of the power of a doublet), decision trees and risk -reward plots for the five locations were established using this approach. The results indicated the POS of geothermal doublet systems at the targeted locations and include the added value of the improved play-based portfolio approach for geothermal development. Especially when the initial POS is low the application of a play based portfolio approach is beneficial over a stand-alone approach.

From these results, it is expected that the distance-controlled portfolio approach offers the potential to evaluate other geothermal targets in a more efficient way. However, not any region is suitable for such portfolio analysis, as targeted geothermal areas must have large geological uncertainty resulting in low to moderate POS (significantly lower than 90 %), yet sufficient spatial correlation in geothermal reservoir properties is expected for the VOI. This requires conceptual models for spatial correlation in reservoir properties or sufficient analogue data/models in adjacent areas, believed to be representative for the studied region.

## 2. Methodology for portfolio analysis

### 2.1. Decision and event tree representation, automated pruning

In former VOI analysis of van Wees et al. Vrijlandt et al. (2020), a portfolio of prospects builds from a binary event tree with branches having a conditional probability for either positive (upside) or negative

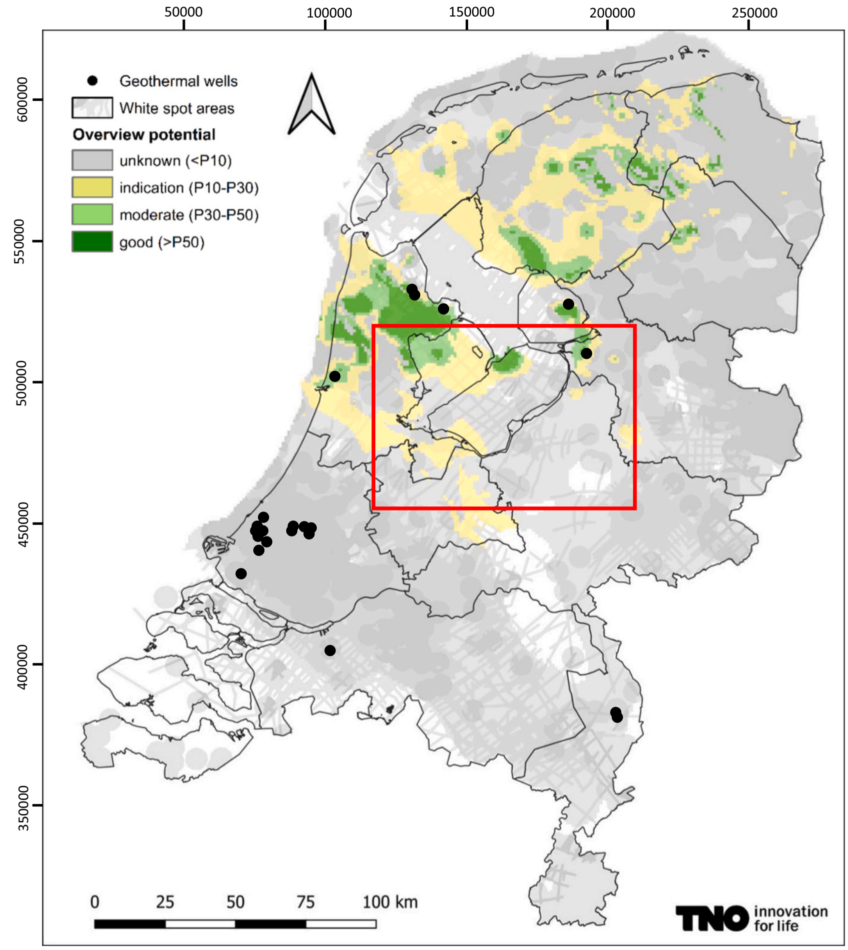


**Fig. 1.** Initial probability of economically feasible doublet systems for the Rotliegend (status 2023) based on Monte Carlo modelling of doublet performance for variability in reservoir permeability and thickness (www.thermogis.nl). Red rectangle = Flevoland area in the central part of the Netherlands (study area). Coordinates are in meters using the RD (Rijksdriehoek) coordinate system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(downside) monetary outcomes. Decision trees for a single asset are relatively simple and their visualization helps in understanding the benefits of VOI and associated exit options (Fig. 2a; Van Wees et al., 2020). In the example decision tree definition of Fig. 2, it is assumed that a pre-drill desk study at moderate costs of 200 k€ can potentially identify if the prospect is marked by a high POS ≥90 % (in close accordance with an "upside" NPV expectation) through extensive study of available existing oil and gas data. Binary trees for a portfolio of multiple prospects become very complex if all decision nodes and outcome branches are visualized. Therefore, following Van Wees et al. (2020) we only visualize preferred options, effectively removing the decision nodes and non-preferred branches (Fig. 2). In addition, we assume that for prospects with a POS exceeding 90 %, the remaining risk is mitigated through an insurance scheme, which is included in the upside NPV calculations. This further reduces the complexity of the tree construction and evaluation (Van Wees et al., 2020). The loss of 400 k€ (Fig. 2a) are the remaining costs which cannot be insured.

In the updated distance controlled VOI method, the application of exit options and pruning of the tree is performed automatically under assumed conditions (i.e. expectation of a negative result). Consequently, the simplified decision tree of Fig. 2b shows preferred decision branches only, and conditional probabilities of the remaining event trees.

### 2.2. Bayesian consistent framework for VOI

In former VOI analysis of van Wees et al. Vrijlandt et al. (2020), a prospect outcome affects the POS of the follow up projects, marked by positive correlation, i.e. when the prospect outcome is successful, the POS of follow-up projects is increased, and when a project fails the POS is lowered.

Appendix A provides the mathematical underpinning for conditional probabilities adopted in the binary trees for multiple prospects. The former VOI method from Van Wees et al., 2020 is described in Appendix A eq. 1 to 7 and Fig. 3, which shows a simplified example for a portfolio of 10 prospects each marked by a POS of 50 % and fixed correlation between prospects, resulting in increase and decrease in POS of 20 % ($\Delta p$=20 % in Appendix A eq. A.7). There are 10 potential projects in this play, but based on the criteria (for success or failure), we only get through to 5 projects (Fig. 3), after which that play is considered worth drilling the other wells or not. We then assume for those successful projects (at 90 % or more), that the remaining wells (out of 10) will be successful. For successful prospects the NPV is assumed to be 1 million € (including insurance for the remaining 10 % risk), and for failure Abortive Exploration Costs (AEC) 3 million € is assumed. In a stand alone development expected NPV is therefore −1 million €. For the portfolio exploiting VOI for timely exit options, the expected NPV is 1.3 million €.

In the update VOI method presented in this paper we adopt a more advanced method for pairwise correlations between prospects compared to the one used in Van Wees et al., 2020. Such distance controlled method is introduced by Bickel et al., 2008, which provides Bayesian mathematical consistency for imperfect information and allows the strength of correlation to vary with distance between prospects and

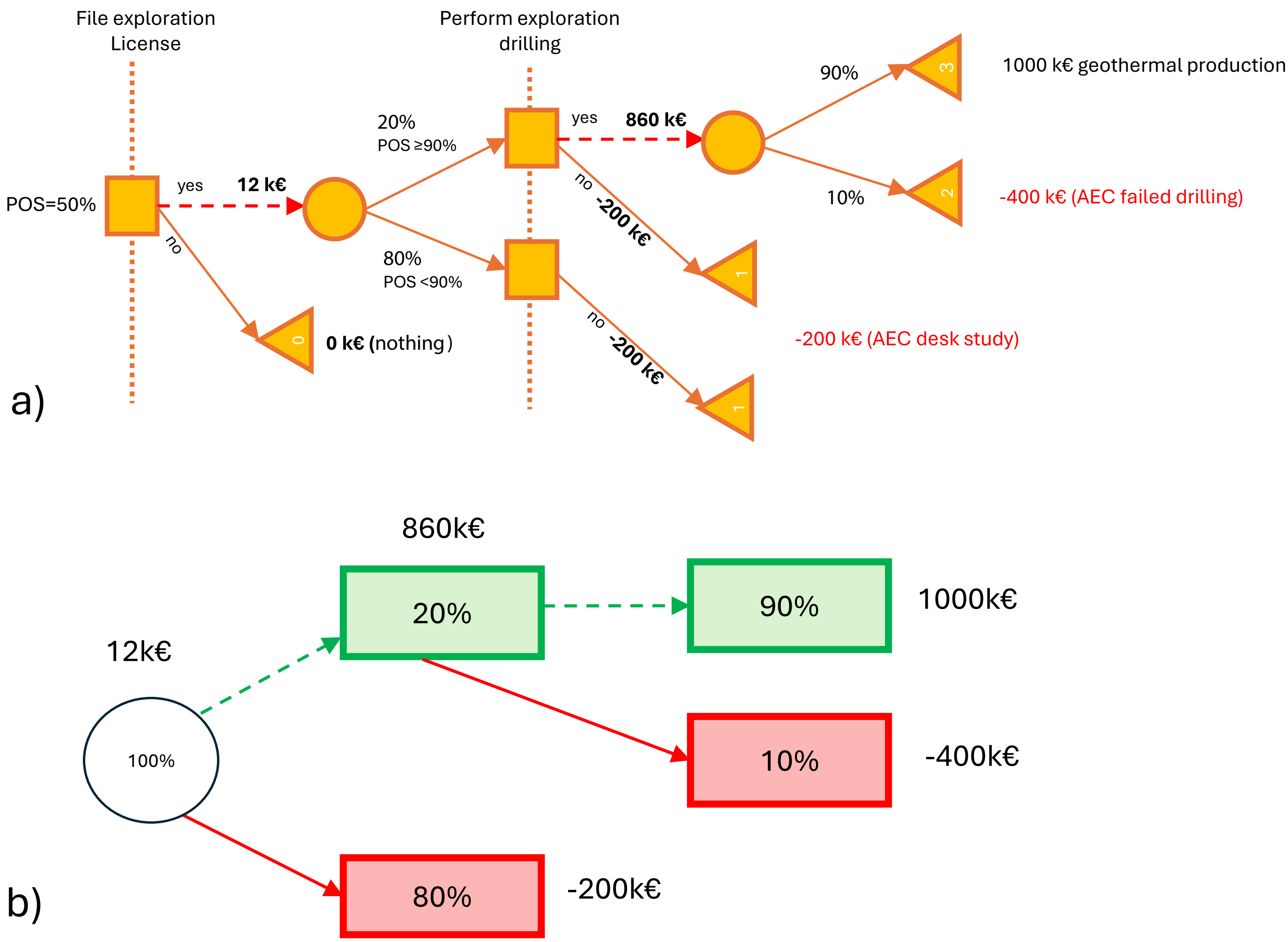


**Fig. 2.** a) Simplified decision tree for the exploration funnel of a single geothermal doublet development in a stand-alone project, marked by an initial POS of 50 %; b) simplified decision tree for the exploration funnel of a single geothermal doublet development in a portfolio project, marked by an initial POS of 100 %. In the tree, time flows from left to right and squares and circles denote decision and event nodes, respectively. The vertical lines mark decision toll gates, and corresponding options are represented by branches flowing from the decision nodes (the preferred branch is dashed red in (a) and green in (b)). Branches flowing from the event nodes mark distinctive possible outcomes beyond control. NPV is determined by weighting the outcomes of the end nodes (triangles) by the probability of the event branches and is rolled back from right to left (after Van Wees et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

preserves marginal probabilities of the prospects in the portfolio, which in turn can vary in the portfolio (for details see Appendix A eq. 8 to 10).

### *2.3. Economic POS, upside and downside from power and NPV expectation curves*

In general, the NPV is defined as the total present value of a time series of cash flows (during the exploration and production lifetime of a geothermal project). The expectation curves for cash flows and NPV are in turn determined by the production flow rate from a production well (Kramers et al., 2012; Van Wees et al., 2012), and expected power [MWth] as:

$$E = Q^{*}C^{*}\Delta T \tag{1}$$

With:

Q  Flowrate [$m^3/s$]

C  Volumetric heat capacity [J/g/K]

$\Delta T$  Exploited temperature drop [°C]

Therefore, in order to define the POS, first the pre-drill expectation of the power of a doublet over its exploration and production lifetime is expressed by a power-expectation curve, which is based on a probabilistic calculation of the product of exploited temperature drop and flow rate (Fig. 4) (Van Wees et al., 2020). The latter depends on reservoir parameters and their underlying uncertainties, in particular the hydraulic transmissivity (product of permeability and reservoir thickness). The steepness of the curve depends on the subsurface uncertainty. A large subsurface uncertainty will be reflected by a large difference between P90 and P10 and a gentle curve slope (Van Wees et al., 2020). The power-expectation curve is subsequently used as input to a techno-economic evaluation to evaluate the NPV over the project lifetime (Van Wees et al., 2012).

In former decision tree analysis, often discrete values are used for NPV and AEC, but in practice potential outcomes are more realistically represented by an expectation curve for NPV (from positive (upside) to negative (downside)), where POS corresponds with the probability of hitting the upside. The updated VOI method presented in this paper uses therefore continuous values for NPV.

In the updated VOI method the marginal POS, and upside and downside (which are constant for each prospect), can be derived in a pre-processing step from the NPV expectation curve (i.e. computed by Monte Carlo simulations). The expected $NPV_{upside}$ is associated with a positive outcome of the prospect where the NPV (associated with the produced power) in the expectation curve is larger than or equal to 0, and is equal to the integral of the NPV values in the upside of the

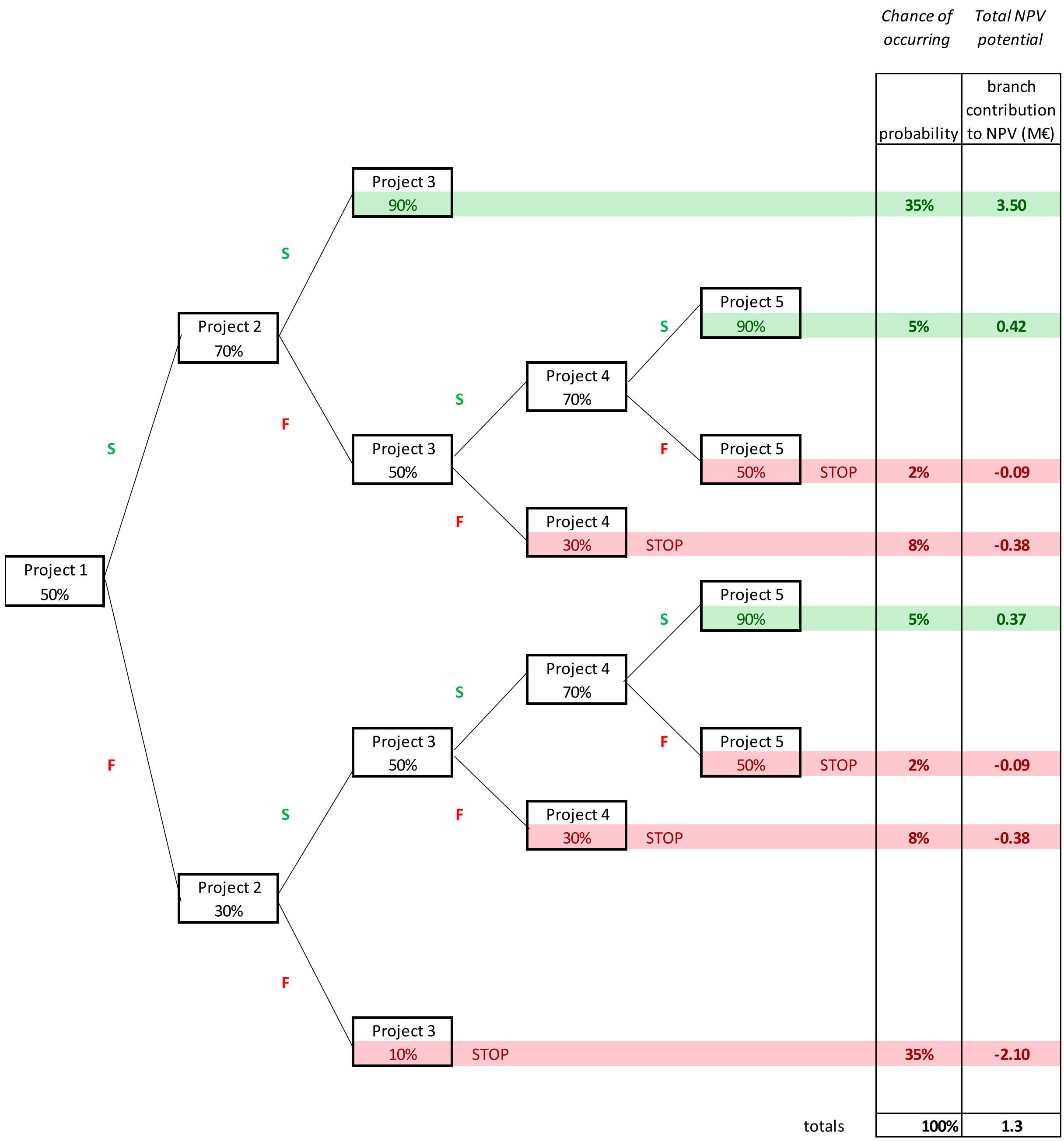


**Fig. 3.** Probability tree for a portfolio of 10 potential prospects with initial POS of 50 % and $\Delta p$=20 % (S: success, F: failure). In the green branches the portfolio is fully developed, in the red branches the portfolio development is discontinued after two failures. Based on the criteria we only get through 5 projects, from which the play is considered worth drilling or not. Demonstrating the approach of former VOI analysis (modified from Van Wees et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

expectation curve (Fig. 5), defined by:

$$NPV_{upside} = \frac{1}{POS}\int_0^{POS} NPV\, dp \tag{2}$$

Where the POS corresponds to 1 minus the *P*-value threshold (e.g., P40) at which the NPV values become positive in the NPV expectation curve. The expected *AEC* is equal to the integral of the NPV values in the downside of the expectation curve (Fig. 5), defined by:

$$AEC = -\frac{1}{(1-POS)}\int_0^{1-POS} NPV\, dp \tag{3}$$

In practice, the POS, $NPV_{upside}$ and $NPV_{downside}$ or AEC can be linearly interpolated from the expectation curve defined from different discrete P outcomes (P10, …,P90). Subsequently, the expected NPV can be defined as done in Van Wees et al., 2020:

$$NPV = POS\, NPV_{upside} - (1-POS)AEC \tag{4}$$

However, if multiple geological factors are used which are not equivalent to the economic POS, then for each of the geological scenario combination of factors a corresponding NPV expectation needs to be given as input and is accumulated over the different scenarios. Such an approach is not considered in this paper.

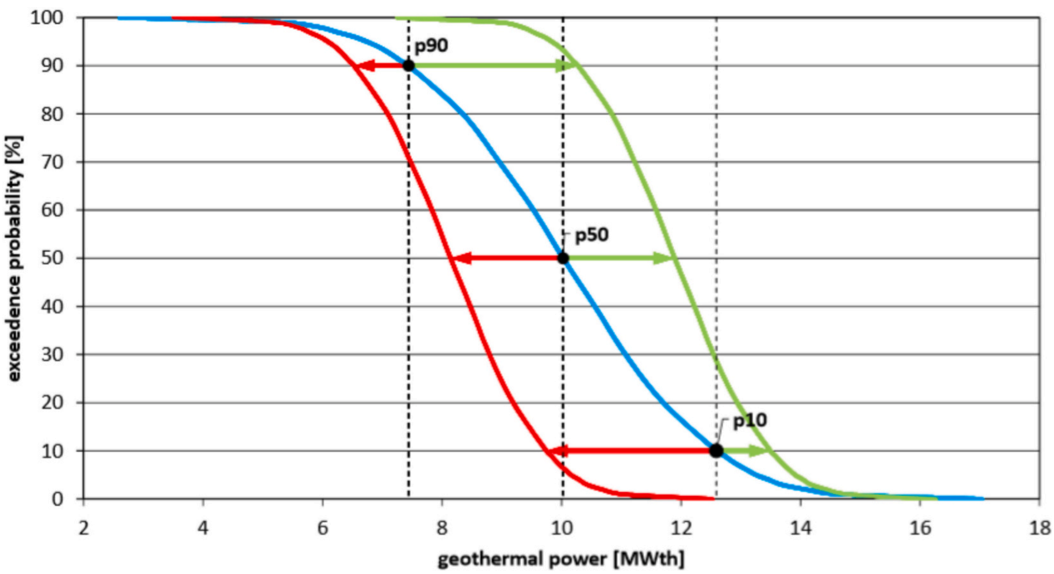


**Fig. 4.** Conceptual power expectation curve (not based on real data). Changing the power expectation curve as a result of increased subsurface data and knowledge. Blue curve: before exploration. Red curve: after exploration, negative result. Green curve: after exploration, positive result (Van Wees et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

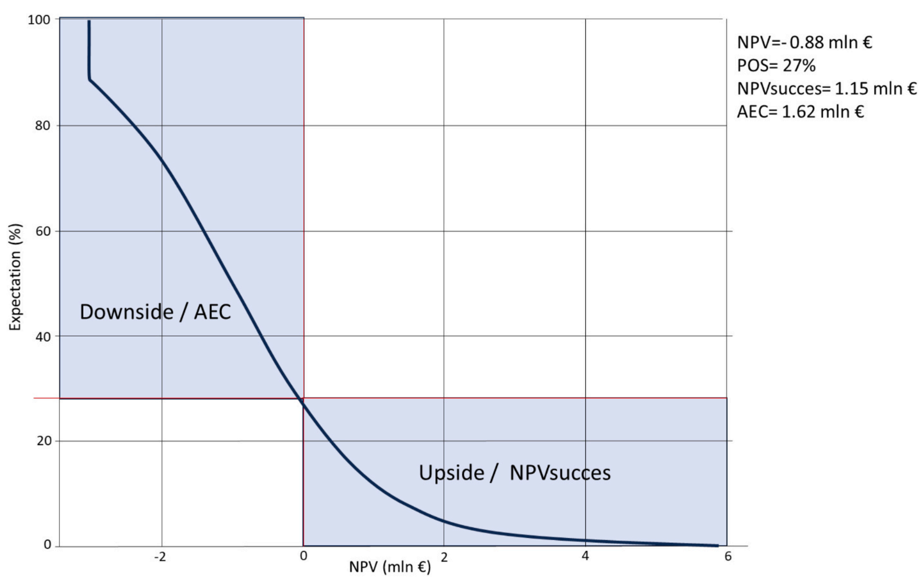


**Fig. 5.** Example of using an NPV expectation curve for determination of upside, downside and POS. Integration is over the vertical axis (dp). In this example the POS is 27 %. Negative NPV outcomes for prognosed exploitation are clipped to AEC = 3 million (mln) € for exploration drilling.

## 3. Application to the Slochteren Formation in the central part of the Netherlands

The VOI methodology is applied to a case study in the Netherlands for the play-based development of the marginal part of the Slochteren Formation in the Flevoland area (Fig. 1).

To steer the selection of areas suited for play portfolio exploration, three conditions need to be considered:

1) sufficient heat demand, 2) presence of a suitable aquifer and reservoir properties for geothermal energy production (considering restricted areas), and 3) subsurface engineering and energy conversion.

Subsequently, we generated maps of POS, upside and downside, and performed the VOI analysis for five target portfolio locations (described in section 4).

### *3.1. Heat demand and repeat potential*

For heat demand in Flevoland we consider heating for existing district heat networks in the cities Almere and Lelystad (Fig. 6). The potential prospect portfolio size, referred to as repeat potential, can be calculated by dividing the heat demand of these cities by the heat supply of a typical doublet, which is around 0.2 PJ/year based on an 11 MWth doublet running 6000 h/year) (Borst et al., 2022).

Currently, the Lelystad city area has a heat network that receives its heat from a biomass plant (92 %). To a smaller extent, natural gas is being used for heating (8 %) (Segers et al., 2020). Lelystad has a heat demand between 0.4 and 1.5 PJ/year with an average of about 1 PJ/year. Dividing this with the heat supply of a doublet of 0.2 PJ/year gives a repeat potential of ca. 5 (Borst et al., 2022).

The city of Almere has a heat network that is largely being fed by natural gas (using an 8.5 km long heat pipeline) from the Diemer gas

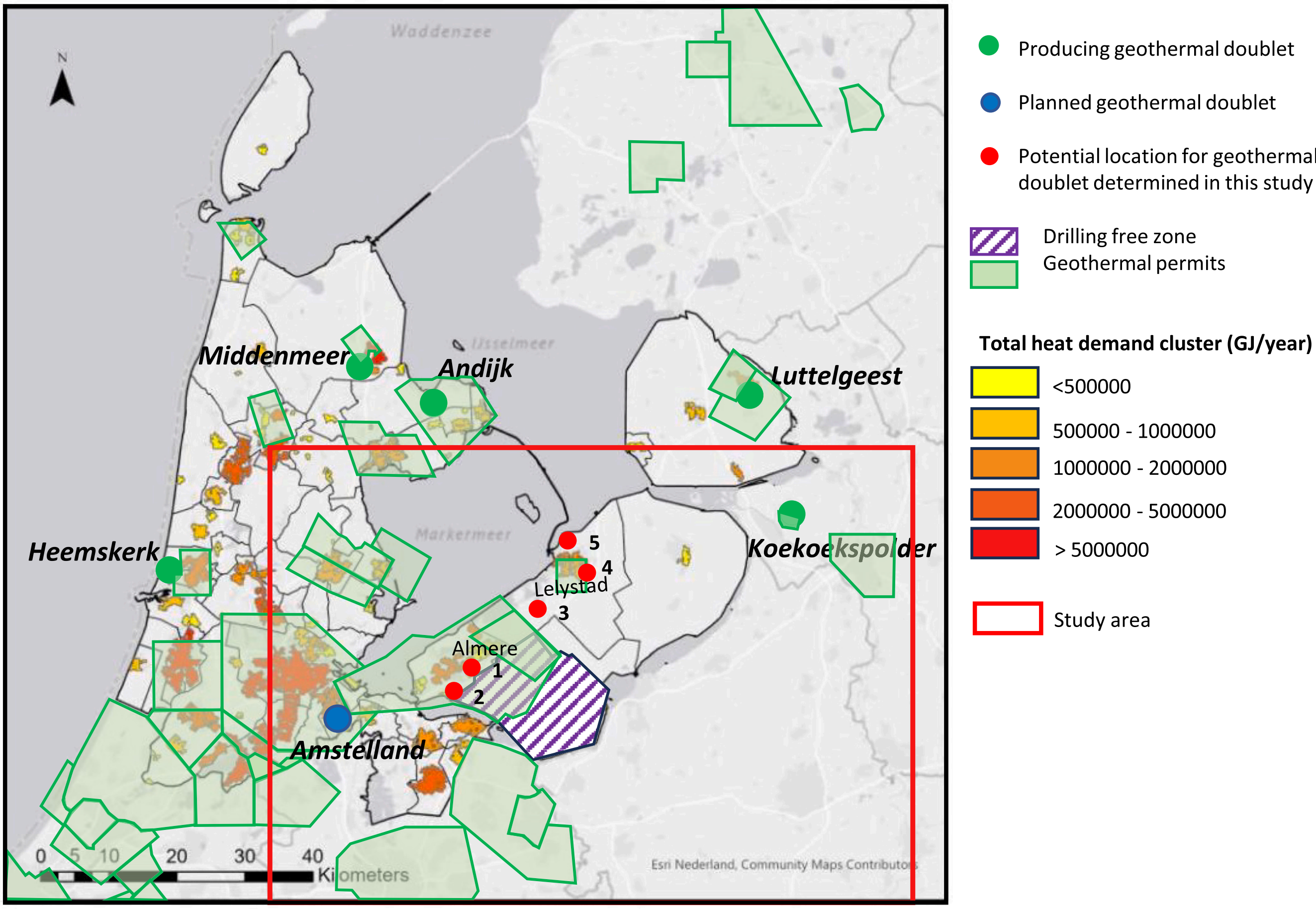


**Fig. 6.** Absolute heat demand clusters with values of >0.2 PJ/year (200,000 GJ/year) for the province of Flevoland and North Holland (modified after Buijze et al., 2019; Borst et al., 2022; Cariaga, 2023, www.thermogis.nl).

plant (covering 96 % of the demand) (Segers et al., 2020). At two locations natural gas auxiliary boilers are installed, which are temporarily used at peak heat demand (4 % of the demand). To a very small extent, solar collectors are used for heating (0.3 % of the demand) (Segers et al., 2020). As a large increase of the built-up area in the Almere region is expected, more (sustainable) heat networks are planned (Segers et al., 2020). The heat demand in Almere varies between 0.4 and 2.3 PJ/year with an average of about 1.3. Dividing this with the heat supply of a doublet of 0.2 PJ/year gives a repeat potential of ca. 6 (Borst et al., 2022).

### 3.2. Rotliegend play

In the selected area, the Slochteren Formation, of Permian age, appears to be the most prospective formation (www.thermogis.nl; Bouroullec et al., 2019; Veldkamp et al., 2022). In the areas surrounding Flevoland, various prospects were successfully developed (Fig. 6). Currently, the nearest producing doublet systems from the Slochteren Formation are those in Luttelgeest (11 wells) and Koekoekspolder (3 wells). To the west (in the province of North Holland) doublet systems are found in Middenmeer (10 wells, but 2 older wells will be abandoned), Andijk (4 wells) and Heemskerk (2 wells) (green dots in Fig. 6) (Buijze et al., 2019). In 2022, a permit has been granted for SCAN (i.e. a government funded geothermal exploration project including over 100 million € investments in seismic acquisition, exploration wells, and extensive subsurface analysis and characterization focused on regions in the Netherlands marked by low data coverage (source: www.scanaardwarmte.nl)) to conduct exploration research to evaluate the geothermal potential in Amstelland, Amsterdam, the Netherlands (blue dot in Fig. 6) (Janszen, 2022; Cariaga, 2023).

Within large parts of the Netherlands, the Slochteren Formation represents an aquifer with good reservoir properties. The Slochteren Formation predominantly consists of aeolian and fluvial sandstones (Gaupp and Okkerman, 2011). Exploration of this reservoir in the central part of the Netherlands has remained limited after the drilling of various dry wells which targeted the Slochteren Formation. This resulted in the area having limited wells and seismic data (see the white spot areas in Fig. 1). Difficulties in pre-drill estimation of the expected flow rates in such areas increases the possibility of drilling an underperforming well, which increases the financial risk.

Reservoir property data of the Slochteren Formation in the Flevoland area and the associated uncertainty therein are required inputs for NPV calculations and the VOI analysis. These data were derived from Veldkamp et al. (2022). The data include depth and thickness, net-to-gross ratios, porosity and permeability (Fig. 7). On www.thermogis.nl depth and thickness maps of the Slochteren Formation are presented, which are based on available well and seismic data from website www.nlog.nl. As well and seismic data is scarce in the study area, large uncertainty remains regarding the reservoir properties especially when moving further away from well and seismic data (Fig. 1). In addition, the ThermoGIS aquifer maps are presented on a national scale, giving a poor representation of regional to local anomalies or deviations (in e.g. facies, tectonic units) for site specific prospecting. In addition, the established property maps in ThermoGIS and this study are subject to uncertainties in burial anomaly, porosity-depth and porosity-permeability relationships (Veldkamp et al., 2022). Large uncertainties in the resulting burial anomalies in the study area are due to: uncertainties in estimates of thickness and erosion, and scarcity of well data. Porosity-depth and

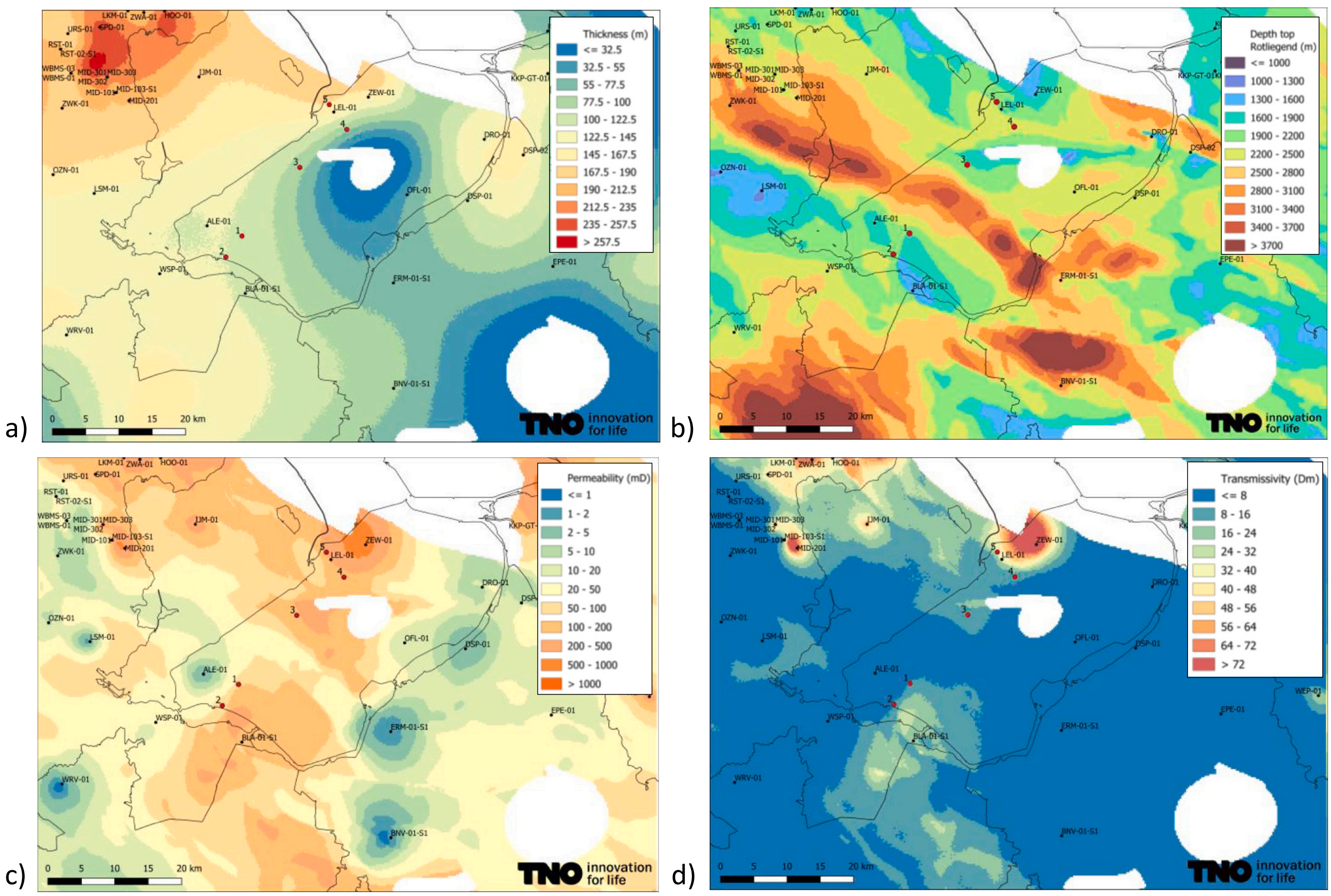


**Fig. 7.** Properties of the Slochteren Formation in the Flevoland area. For the extent and coordinates of this area see red rectangle in Fig. 1: a) thickness map; b) depth top map, c) permeability map, and d) transmissivity (P50) map (including potential locations for geothermal doublet systems with red dots). These maps have been constructed by the use of the burial anomaly, thickness and top depth maps, and porosity – depth and porosity – permeability regression parameters from Veldkamp et al. (2022). The wells used for establishing these property maps are: ALE-01, BLA-01-S1, BNV-01-S1, DRO-01, DSP-01, DSP-02, EPE-01, ERM-01-S1, HOO-01, IJD-01, IJM-01, KAM-01-S1, KGB-01, KKP-GT-01, KKP-GT-02, LEL-01, LSM-01, OFL-01, WEP-01, WYH-01, ZEW-01 and ZWA-01. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
Detailed property values and locations in RD of 5 localities with high geothermal potential. SW-Flevoland = Location 1 and 2, W-Flevoland = Location 3, and NW-Flevoland = Location 4 and 5 (see Fig. 7).

| Portfolio Location | X | Y | # potential prospects | Porosity [%] | Permeability *k* [mD] | Net to gross NTG [−] | Top Depth *Z* [m] | Thickness *H* [m] | Transmissivity *kH* [Dm] | Temperature at mid aquifer depth T [°C] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 147,099 | 486,007 | 6 | 16.7 | 81 | 0.98 | 1932 | 119 | 9.6 | 72 |
| 2 | 144,738 | 482,787 | 6 | 16.7 | 80 | 0.97 | 2032 | 122 | 9.8 | 75 |
| 3 | 155,799 | 496,320 | 6 | 18.5 | 180 | 0.94 | 1970 | 86 | 15.5 | 72 |
| 4 | 162,906 | 501,999 | 5 | 18.5 | 169 | 0.93 | 2258 | 81 | 11.1 | 81 |
| 5 | 160,315 | 505,772 | 5 | 19.2 | 184 | 0.97 | 2140 | 164 | 30.2 | 79 |

porosity-permeability relationships were derived by using regional well data, taking into account maximum burial, structural setting and facies. These relationships differ strongly from the national ones used in ThermoGIS. Thereby, reducing the uncertainty in these relationships for the study area.

The Slochteren reservoir thickness varies between 125 m in the southwestern part of Flevoland and 170 m in the northwestern part (Fig. 7a). The reservoir top depth is around 2000 m (Fig. 7b). The average geothermal gradient in the Netherlands is about 31 °C/km with an average of 10 °C surface temperature (Bonté et al., 2012; Békési et al., 2020). The resulting average temperature at mid-reservoir depth will then be approximately 75 °C. The reservoir porosity is about 15 % in the south to southwest and up to 25 % in the northwest of Flevoland. The Rotliegend is developed in aeolian facies (Fryberger et al., 2011) and net-to-gross values between 95 and 100 % are determined in the south, west and northwest parts of Flevoland.

The rocks of the Slochteren Formation around Lelystad have an excellent permeability (up to 800 mD) and large thickness, resulting in a very good transmissivity exceeding 30 Dm (Fig. 7c, d). However, the southwestern part of the province, around Almere has very low expected permeabilities of 1–2 mD based on an evaluation of the ALE-01 well. The resulting transmissivity is therefore very low, around 0.1 Dm (Fig. 7c, d). The expected geothermal potential is also low. However, higher potential is expected in southeastern Flevoland, with maximum permeability values of about 70 mD based on the nearby BLA-01 well, and transmissivities around 10 Dm (Fig. 7d).

The reported permeability values are for horizontal flow ($k_h$). For the calculation of well injectivity and productivity in deviated wells, the permeability anisotropy ($k_h/k_v$) is important. Peters et al. (2015) proposes log derived permeability anisotropy ratios between 2 and 20 in a study on property characteristics of geothermal injection wells. In this study we adopt an average anisotropy of 10.

Based on the reservoir characteristics and the surface potential (heat demand and drilling-free zones), five locations for potential geothermal doublets are indicated in Fig. 6 and 7. Table 1 lists the exact position and property values at these locations. An threshold value of 5 Dm is applied to avoid the most likely uneconomic flow rates (Mijnlieff, 2020). All five selected locations conform to this requirement (Table 1).

### 3.3. (Sub)surface engineering and asset performance assessment

#### 3.3.1. Technical aspects

The NPV calculations were made for standardised doublet system layouts in the five targeted prospect portfolio locations between and around Lelystad and Almere, which can be connected to the existing heat networks (Fig. 6). For the NPV assessment, we used a technical- and cost-engineering model (Kramers et al., 2012; Van Wees et al., 2012; Vrijlandt et al., 2020; www.thermogis.nl).

Geothermal energy production in a doublet system is marked by a producer and injector well, forming a loop for the produced brines, which are fully reinjected. At the top side a heat exchanger allows the extraction of geothermal energy which can be used for direct heating, or for absorption cooling. The re-injection assures that during production, pressure support is maintained in the aquifer.

The most important results from the technical analysis, which serve as input to the NPV calculations, are the power [MW] and flow rate at the reservoir level which can be approximated by the following equation (Van Wees et al., 2012):

$$Q = \Delta p \frac{\pi\, kH}{\mu\left(ln\left(\frac{L}{r_w}\right) + S\right)} \tag{5}$$

With:

$Q$ flow rate [$m^3/s$]

$\Delta p$ pressure difference between injector and producer to drive the flow in the reservoir [Pa]

$k$ permeability [$m^2$]

$H$ aquifer thickness [m]

$\mu$ viscosity [Pa·s]

$L$ distance between injector and producer [m]

$r_w$ well radius [m]

$S$ skin factor [−].

In general, the flow rates in the wells are relatively high to ensure that the thermal losses along the wellbore are 1–2 °C at the top side. The distance between the well perforations at the aquifer depth should be chosen such that the produced waters are marked by a reduction in temperature which is preferably negligible during the economic lifetime of the doublet.

The technical input is based on maps and estimates of depth, thickness, net-to-gross and permeability (section 3.2). The temperature is based on the Dutch 3D temperature model, where each cell holds an estimate of the temperature specified for the characteristics of the Dutch subsurface (source: www.thermogis.nl/en/temperature-model).

For the doublet calculations, we adopted a well design tailored to the sometimes relatively poor reservoir transmissivity as outlined in the previous section. To this end, the injection well has a high inclination at the reservoir depth for achieving a large contact area with the formation and therefore an optimal injectivity. The producer well has been chosen to be vertical as productivity for a specific well design is typically significantly higher (up to 100 %), compared to injectivity due to the strong increase of brine viscosity as an effect of cooling of the brine. For the injector, the skin factor was roughly −4 for the sub-horizontal scenario, based on analytical approaches (source: www.nlog.nl/en/tools). The assumed internal diameter of the well casing is 8.5″.

The pump pressure is being optimized based on the State Supervision of the Mines (SodM) protocol (SodM, 2019). This is done by optimizing the pump pressure to a minimum cost price per unit energy produced.

In the Netherlands very saline brines (up to 180,000 ppm) are produced by some doublets. The salinity $s$ (ppm) is depth dependent and determines among others the density and viscosity of the produced water, and necessary pump pressure. The salinity is based on the following equation:

$$s = \left(s_0 + s_{grad}\left(z + 0.5H\right)\right) \tag{6}$$

With:

s aquifer salinity [ppm]

$s_0$ aquifer salinity at z = 0 [ppm]

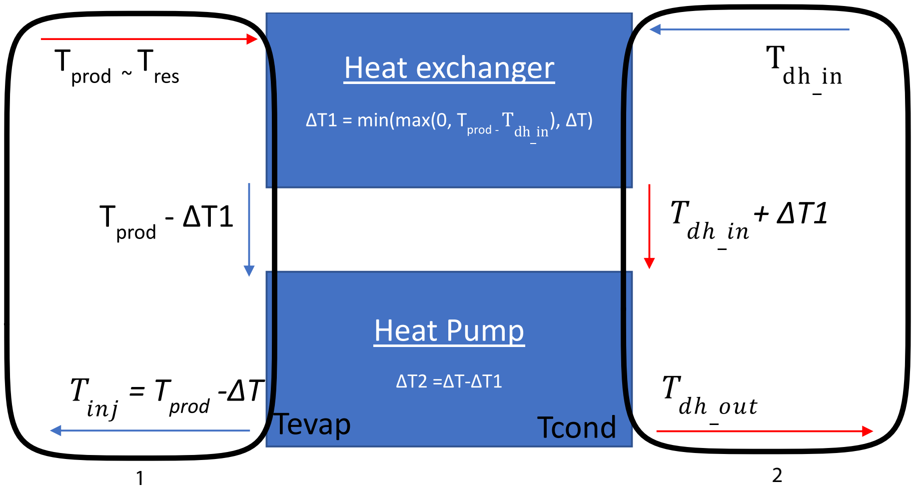


**Fig. 8.** Schematic of the heat pump/heat exchanger system (www.thermogis.nl). $T_{prod}$ = production temperature, $T_{aq}$ = aquifer temperature, $T_{dh\_in}$ = inlet temperature of the district heating network, $T_{dh\_out}$ = outlet temperature of the district heating network, $T_{inj}$ = injection temperature (after www.thermogis.nl).

$s_{grad}$ aquifer salinity gradient (47) [ppm/m]
z aquifer top depth (from mapping) [m]
H aquifer thickness (from mapping) [m]

The well trajectory curvature is used in order to calculate the along hole length of the wells this is done by the following equation:

$$Along\ hole\ length = \left(s_{curve} * \sqrt{(TVD)^2 + \left(\frac{1}{2} d_{well}\right)^2}\right) \quad (7)$$

With:
$S_{curve}$ Well trajectory curvature factor (1.1) [−]
TVD True Vertical Depth [m]
$D_{well}$ Well distance [m]

Based on these input parameters and equations a priori-NPV calculations were made by the use of the ThermoGIS tool i.e. a national geothermal resource information system for the Netherlands (www.thermogis.nl). This tool is complemented with an extension for an industrial heat pump (section 3.3.2), and tailored to the heat supply for district heating in this region. The calculated expectation curves for NPV were subsequently used to determine the economic POS, upside and downside of a geothermal doublet, at each map location.

### 3.3.2. Heat pump concept

Fig. 8 gives a schematic representation of the adopted heat pump system used for our NPV calculations. The left side (Fig. 8 box 1) demonstrates the primary circuit of the geothermal brine. In this system the production temperature ($T_{prod}$) is assumed to be equal to the aquifer temperature ($T_{aq}$). The production temperature is then lowered in the heat exchanger by ΔT1. When entering the heat pump this temperature is lowered by ΔT2 to the injection temperature ($T_{inj}$). The right side (Fig. 8 box 2) demonstrates the district heating network. Here, the cool water returning from the district heating network ($T_{dh\_out}$) is first heated in the heat exchanger to $T_{dh\_out}$ + ΔT1. Subsequently, it is heated by the heat pump to the heat network inlet temperature ($T_{dh\_in}$). The heat pump option allows for lower injection temperatures than specified by the return temperature of the district heat network (i.e. $T_{dh\_in}$, the inlet temperature of the heat exchanger/ heat pump). It is assumed that the injection temperature $T_{inj}$ is chosen to be as low as possible to maximize geothermal power, but is limited to a maximum offset $T_{inj}$ = $T_{res}$- ΔT, where ΔT is set to 40 °C in accordance with recommendations from SodM (source: www.thermogis.nl/en/heat-pumps).

For the heat pump concept adopted in our study, we assume that the temperature of the produced water from the reservoir (with temperatures between 72 and 81 °C see table 1) is used as source in the heat pump to elevate district heating network supply temperatures to 80 °C. The heat pump outlet temperature into the heat network will thus be 80 °C and we assume a heat pump inlet temperature from the heat network of 45 °C. In addition, the $T_{inj}$ was chosen as low as possible. With a ΔT of 40 °C the $T_{inj}$ reaches a minimum of 5 °C.

The coefficient of performance (COP) of the heat pump is calculated based on the heat network inlet temperature (i.e., $T_{dh\_out}$, the outlet temperature of the heat exchanger/heat pump) and the injection temperature of the brine. The COP of the heat pump is given by the following equation (www.thermogis.nl):

$$COP_{hp} = \eta_{rel}\ (T_{dh\_out} + 273.1 + 3) / ((T_{dh\_out} - T_{inj} + 6) \quad (8)$$

With:
$COP_{hp}$ coefficient of performance of the heat pump [−]
$T_{dh\_out}$ outlet temperature of the heat exchanger/heat pump [°C]
$\eta_{rel}$ relative efficiency of the heat pump [−]
$T_{inj}$ Injection temperature [°C]

Where $\eta_{rel}$ is 0.6, and it is assumed that condenser and evaporator temperatures of the heat pump are, respectively, 3 °C lower and higher than the source and outlet temperature of the heat pump.

The power corresponds to geothermal thermal power, which corresponds to the product of flowrate, ΔT, and volumetric heat capacity of the brine. The COP corresponds to the ratio of produced final thermal power (which is equal to the geothermal power, topped up by the electricity consumption in the heat pump) and the sum of power consumption in the heat pump and Electrical Submersible Pumps (ESP). Please note that the $COP_{hp}$ accounts for the heat produced in the heat pump only. If $T_{prod}$ > $T_{dh\_in}$ part of the heating is provided by a heat exchanger and only the remaining part is accomplished by the heat pump, such that the COP in the heat pump scenario can be significantly higher than $COP_{hp}$ (Fig. 8).

Furthermore, brine production involves Electrical Submersible Pump (ESP) for production and reinjection of the fluids, with efficiency of $ESP_{n.}$ and the parasitic power needed in the heat conversion process:

$$E_{consup} = Q\ \frac{\Delta p}{ESPn.} \quad (9)$$

With:
$E_{consup}$ power [MW]
Q flow rate (200) [$m^3$/h]
$\Delta p$ Pressure for driving the thermal loop [bar]
$ESP_n$ Electrical Submersible Pump system efficiency (0.6) [−]

The lead times for design and construction, and testing a doublet system are in the order of months and days, respectively.

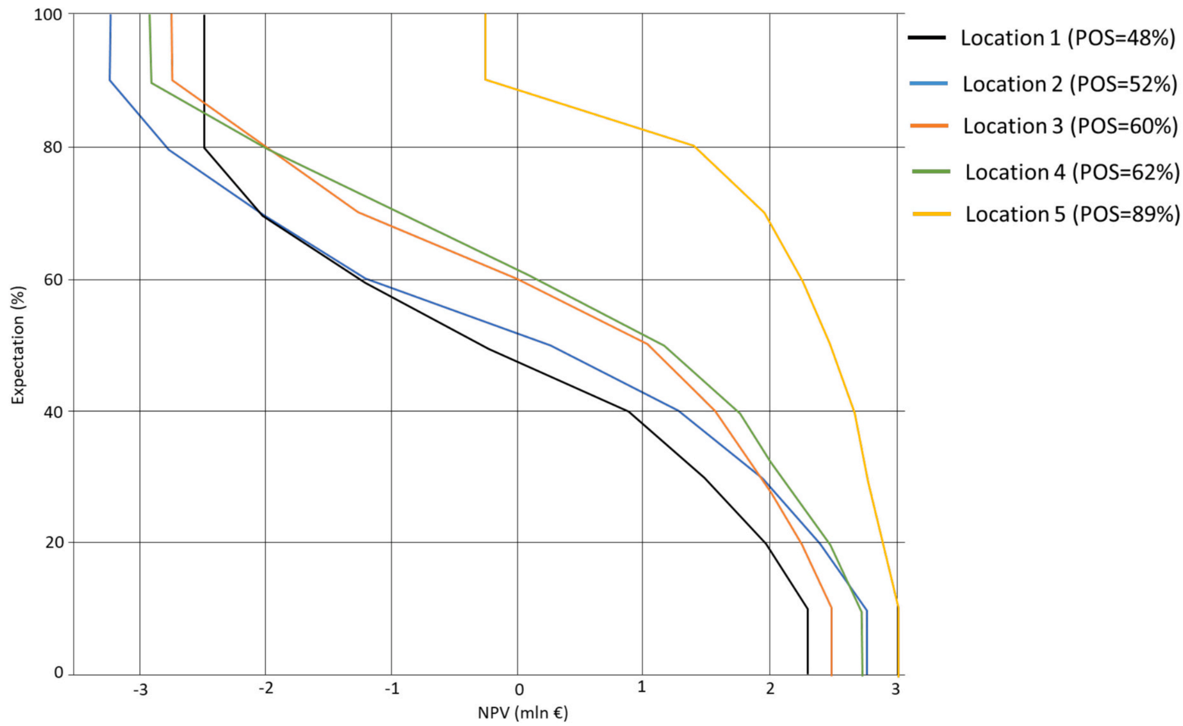


**Fig. 9.** NPV expectation curves for each portfolio location. Below 10 % the lines are vertical as abortive exploration costs are reached, and above 90 % the lines are vertical as it is presumed that the business case will not further increase significantly.

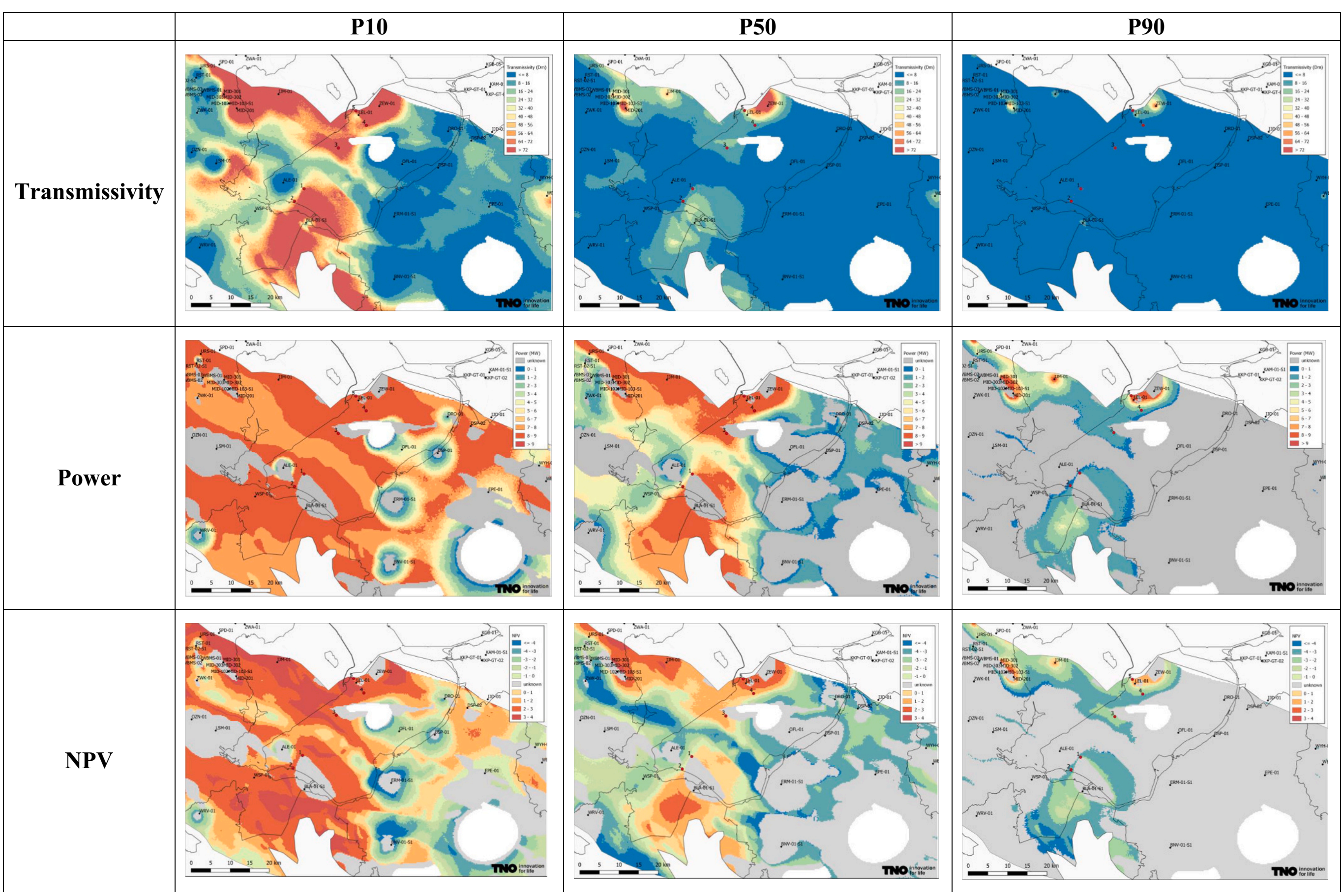


**Fig. 10.** P10, P50 and P90 calculated transmissivities, power and NPV values of a doublet system (million €).

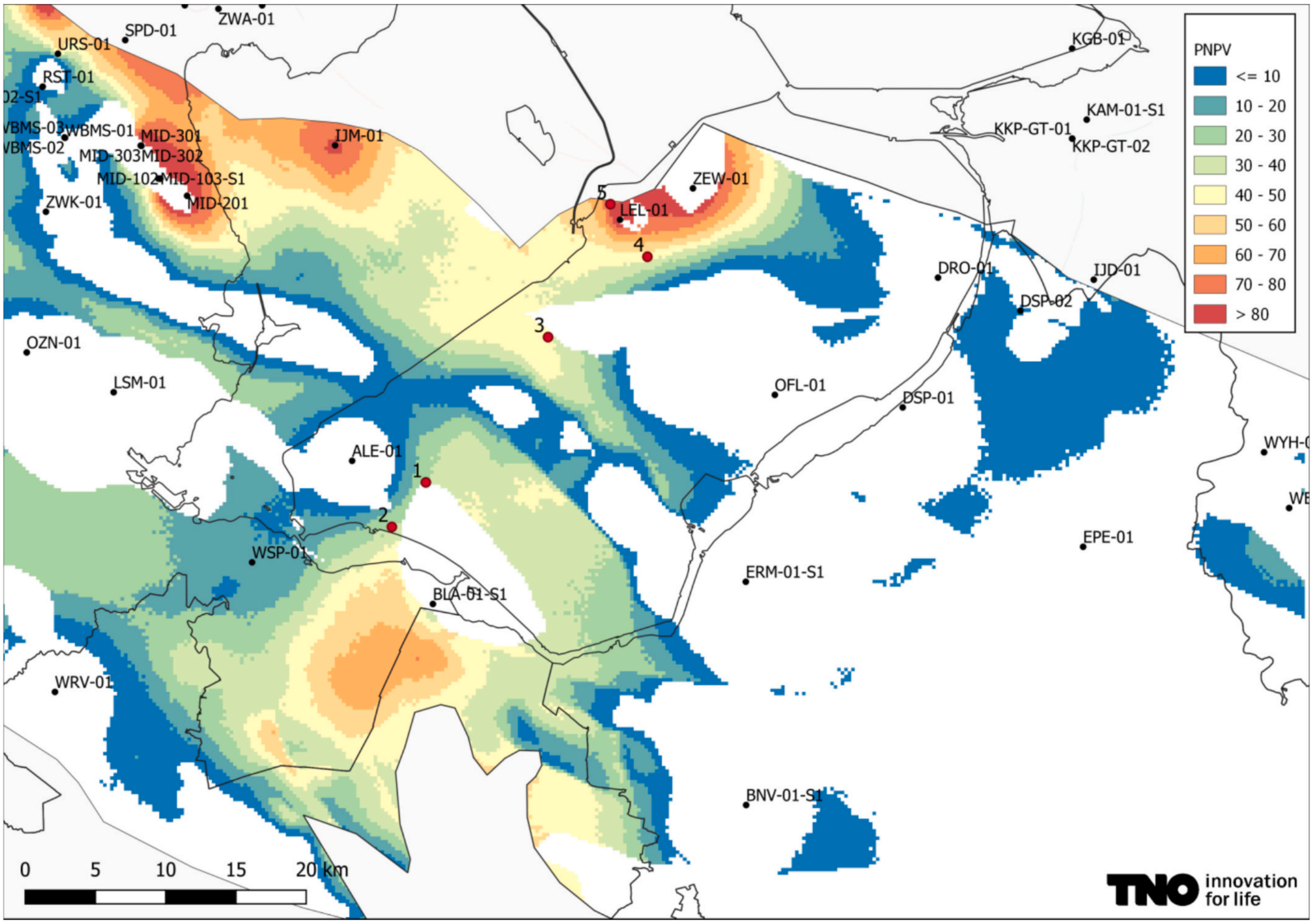


**Fig. 11.** Initial marginal POS.

### 3.3.3. *Economic aspects*

The costs associated with geothermal production is based on a discounted cashflow model, which assumes that the payback period of the investment is in 15 years. This model calculated the cost price per energy unit [€ct/kWh] (www.thermogis.nl). It must be noted that not too much detail can be given on the values of the economic input parameters due to confidentiality reasons.

The CAPEX includes the depth dependent well costs and remaining (installation)costs. The CAPEX is calculated with an average total cost of the wells (well construction, completion, and testing) and a quadratic function of True Vertical Depth (TVD) of the reservoir, shown in the following relation:

$$CAPEX_{wells} = 375,000 + 1050 \bullet s_{curve} \bullet z_{tvdtop} + 0.3 \bullet s_{curve} \bullet Z^2{}_{tvdtop} \quad (10)$$

With:

$CAPEX_{wells}$ average cost of the well [€]

$z_{tvdtop}$ True Vertical Depth (TVD) of the top of the reservoir measured from the surface (from mapping) [m]

$s_{curve}$ curvature factor to correct (in this study 1.1) [−].

In addition, to the costs for the wells, costs for an ESP need to be included. A single ESP is considered sufficient to drive the thermal loop. Note that the numbers in the formula of eq. 10 are practical numbers based on Dutch experience.

The Operating Expenditures (OPEX) depends on the power of the installation [100€/kW] and the amount of produced energy [19€ct/kWh]. Additionally, the electricity costs for driving the pump are being calculated.

Subsequently, the economic potential can be calculated by comparing the cost price from the discounted cashflow model with a reference price. The reference price is 51 €/kWh, which is the SDE++ – reference price for geothermal energy in 2021 (www.thermogis.nl/en/economic-model). From this the following classes can be defined:

- Unknown: P10 cost price > reference price
- Indication: P10 cost price < reference price
- Moderate: P30 cost price < reference price
- Good: P50 cost price < reference price

Indicating that the reference price strongly influences the economic potential.

## 4. Results

### 4.1. *NPV, prior POS, upside and downside*

NPV expectation curves are based on realistic calculations of techno-economic performance (and therefore POS), which are assumed to be affected through various geological parameters used as input to the calculations. The calculated NPV expectation curves are closely associated to the produced power (Fig. 9). These expectation curves can be read from probability values of NPV at a particular location from map input values (Fig. 10 and 11). They are subsequently linked to a marginal POS (expectation at NPV = 0), an associated upside (NPV above 0) and downside (NPV below 0) of a doublet at each portfolio location (Fig. 11 to 13).

The updated play-based portfolio approach uses uncertainties in

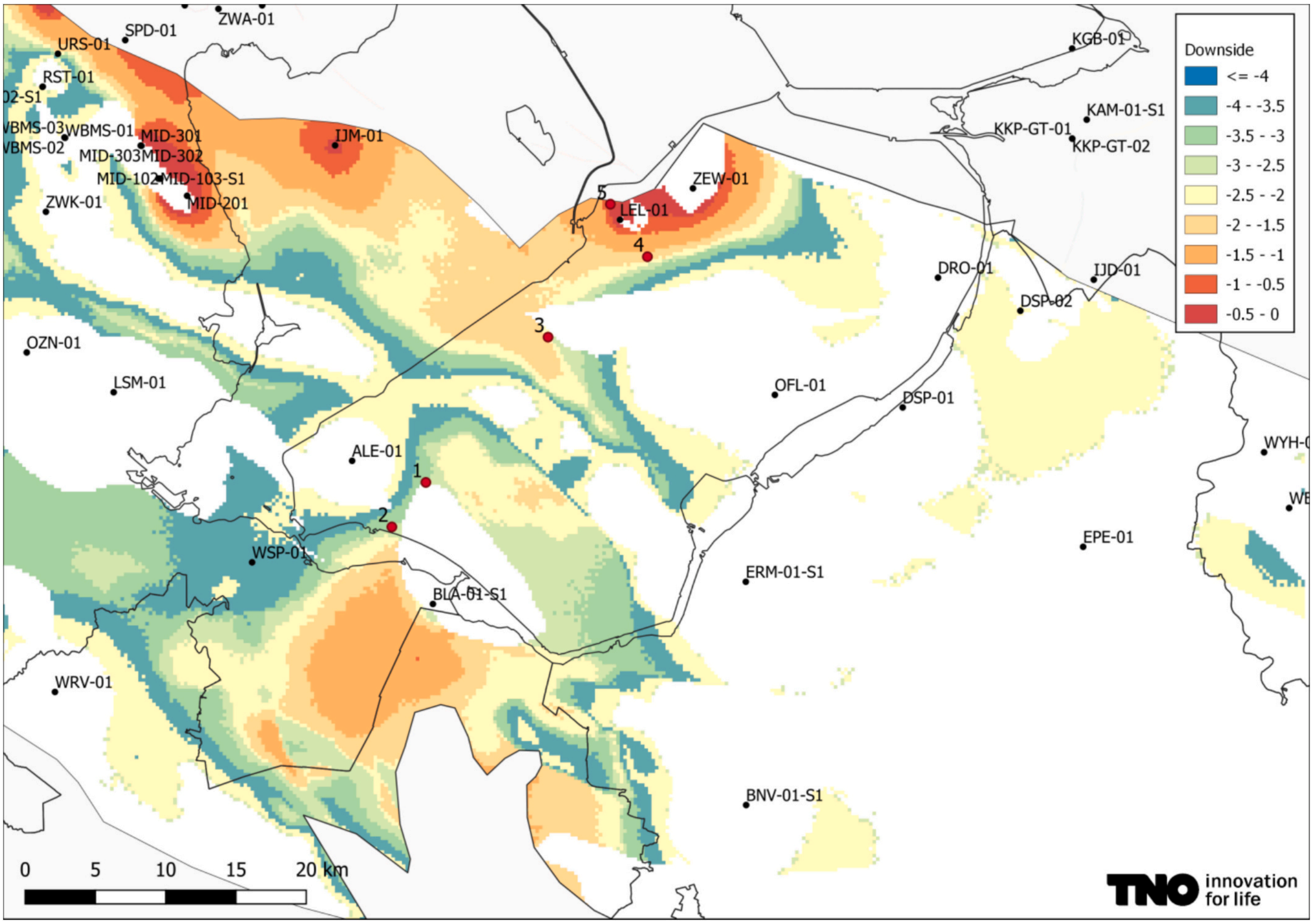


**Fig. 12.** Downside determined from the P10 to P90 outcomes of NPV.

geological factors as influencing parameters affecting the expectation curves for cash flows and NPV. The productivity of a reservoir depends mostly on its permeability and the thickness. Therefore, the estimated transmissivity is among the most important geological factors influencing the NPV and POS. The calculated transmissivity in SW-Flevoland is around 2 Dm (P90) and 10 Dm (P50), whereas in NW-Flevoland the transmissivity is around 11 Dm (P90) and 34 Dm (P50) (Fig. 10). The calculated power in SW-Flevoland is around 0.9 MW (P90) and 6 MW (P50), whereas in NW-Flevoland the power is much higher with values between 2 and 7 MW (P90) and 8.3 MW (P50) (Fig. 10). The expectation curves demonstrate POS values of around 50 % in SW-Flevoland, of around 60 % for location 3 and 4, and of almost 90 % for location 5 (Fig. 9). Additionally, the calculated NPV in SW-Flevoland is around −3 million € (P90), −0.1 million € (P50) and 2.4 million € (P10), whereas in NW-Flevoland the NPV is around 0.1 million € (P90), 2.5 million € (P50) and 3 million € (P10) (Fig. 10). Thus, as expected, an increased transmissivity can be linked to an increased power, POS and NPV.

### *4.2. VOI Analysis*

For the updated VOI analysis we adopt a distance-controlled conditional probability approach with correlation coefficients determined as a distance function (Appendix A eq. A.9). The VOI analysis was applied to the five selected portfolio locations in Flevoland. Each portfolio location includes 5 doublet prospects that will be developed consecutively. For each location we compared two scenarios with correlation strengths k = 0.2 and k = 0.3 to highlight the sensitivity of the correlation strength, even when the k-values are chosen close to each other, on the risk and reward of the prospect portfolio. When the k value is closer to 0 (perfect information) it has a stronger spatial correlation compared to a k closer to 1 (imperfect information). From the risk-reward plot (Fig. 14) and the decision trees (Appendix B) it can be concluded that a (slightly) lower k value and therefore a higher correlation strength contributes significantly to the business case with lower risks and higher reward. The resulting probability trees of the improved VOI method are shown in Appendix B. The trees have a starting POS of 100 %. In all trees an increase in distance learning associated with a lower k-value, results in a faster risk reduction (see Fig. 14 difference between k = 0.2 and k = 0.3). This is associated with more elaborated (longer decision trees) when the k = 0.3 compared to a k of 0.2. The decision trees also show that the VOI is largest when drilling the first prospect and decreases when progressing deeper in the trees (Appendix B).

The use of strongly spatially correlated properties adopted in this study is supported by geothermal development in the Netherlands, which is marked by many successful runner-up doublet systems in a restricted area in a geothermal play, once the first project had been successful. For the Rotliegend play this is exemplified by geothermal wells drilled in the Middenmeer and Andijk areas in the northern part of the province of North Holland.

The risk versus reward for each location has also been plotted for the stand-alone approach to compare such stand-alone approach with a play-based portfolio approach (Fig. 14). For the stand-alone approach, reward is defined as the Expected Monetary Value (EMV) or NPV taking into account both success and failure outcomes: NPV = ($NPV_{succes}$*POS-Risk)*portfolio size (equation from Van Wees et al., 2020). Risk is defined as the expected losses: ((1-POS)*AEC)*portfolio size (equation

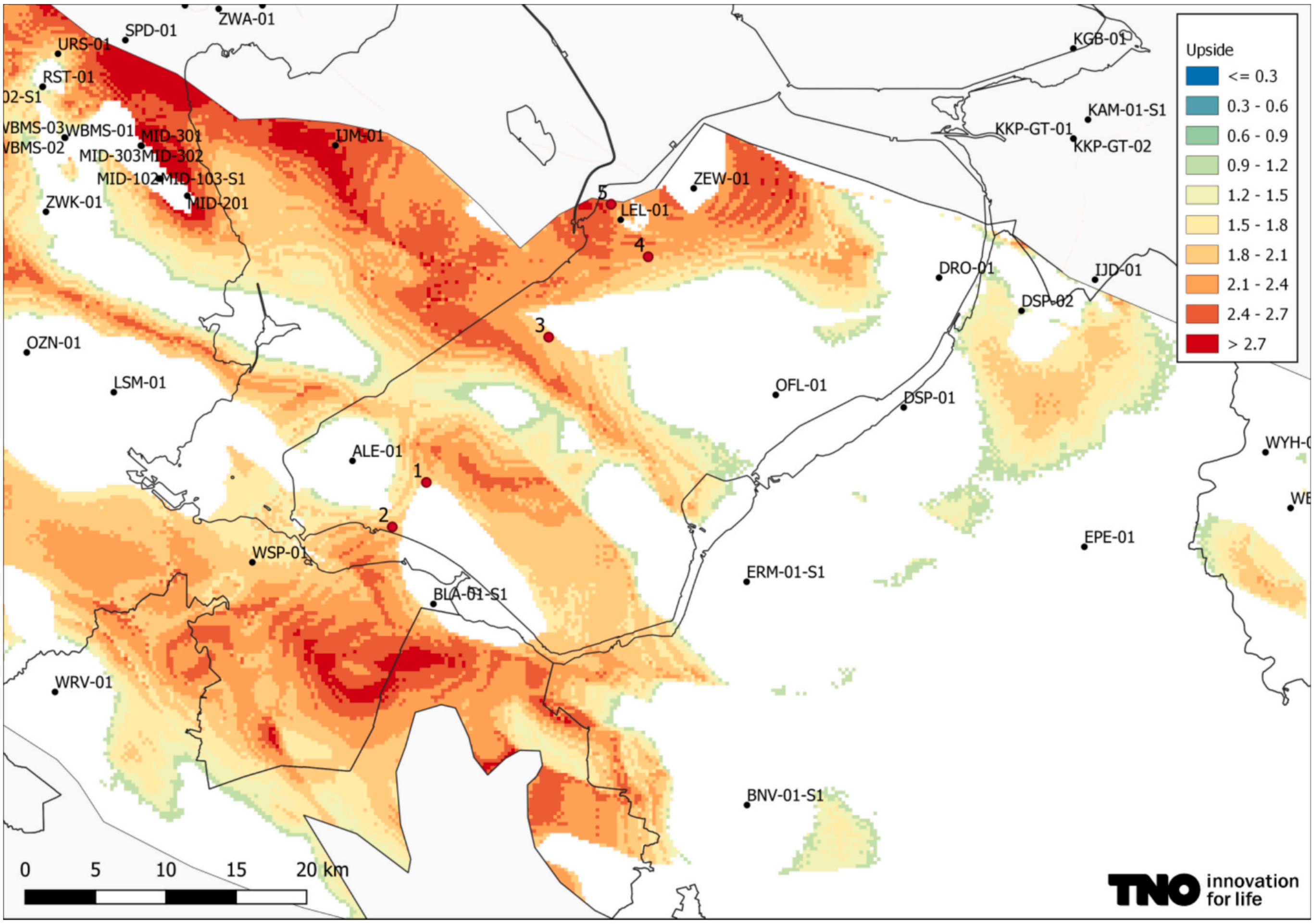


**Fig. 13.** Upside determined from the P10 to P90 outcomes of NPV.

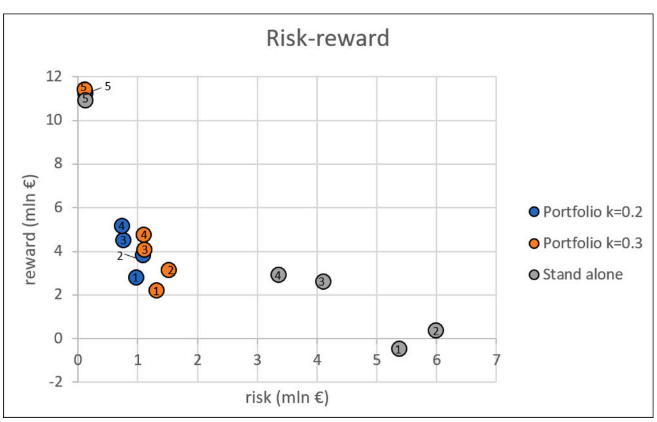


**Fig. 14.** Plot demonstrating the influence of k-value on the risk and reward of the play-based prospect portfolio, and the difference in risk (plotted positively) and reward between the portfolio and stand-alone approach. Numbers at dots are the portfolio locations.

from Van Wees et al., 2020). The portfolio size for locations 1, 2 and 3 is six and for locations 4 and 5 is five.

In SW-Flevoland the downside for the stand-alone approach reaches values of −5 to −6 million € (locations 1 and 2), whereas in NW-Flevoland the downside (risk) is less with values of −3 to −4 million € (locations 3 and 4) and − 0.8 million € (location 5) (Fig. 12). In SW-Flevoland the upside is marked by values of ca. 0 million € (locations 1 and 2), to ca. 2 million € (locations 3 and 4), whereas in NW-Flevoland the upside is higher with values of up to 2.5 million € (location 5) (Fig. 13). In summary, for locations 1–4, the prognosed reward is ranging from 0 to 2 million € with an associated risk of 3–6 million €, depending on development location. This is a highly unfavourable risk-reward ratio of ca. 3 and hampers further development. This implies that such a prospect can only yield a positive business case when a significant financial stimulus is provided to increase the reward and/or mitigate the risk.

For the portfolio approach, for locations 1–4 the risk-reward ratio is significantly lowered to ca. 0.25 (Fig. 14). For these locations, the play-based portfolio approach demonstrates much lower risk and higher reward when compared to the stand-alone approach (Fig. 14). Once the first prospect is successful, the portfolio yields a progressively positive business case after each positive outcome. This is visible when progressing deeper in the trees (Appendix B). Consequently, the portfolio yields a progressive positive business case after each positive outcome.

The results clearly demonstrate the benefits of the portfolio approach compared to the stand-alone approach. The portfolio approach provides higher rewards and lower risks, especially visible for initially low POS projects. From the risk-reward plot it is visible that when the initial POS of a prospect gets too high a portfolio approach is less suitable, as can be determined by the very low risk and very high reward at location 5 (Fig. 14). Location 5 (with very high initial POS of 88 %, see also Appendix B) has a similar risk-reward ratio for each scenario (play-based portfolio and stand-alone approach), and therefore a play-based portfolio approach has no added value and the stand-alone approach is favourable at this location (Fig. 14).

## 5. Discussion

For geothermal play-based portfolio analysis, the method deployed in this paper considers the effect of imperfect information, where correlation strength is expected as a function of distance between prospects. This is more advanced compared to the former VOI method where a simple positive correlation (fixed increase or decrease) for follow up prospects is assumed. The new method takes into account the spatial geological correlation between prospects. The method uses continuous values for the NPV marked as an expectation curve for NPV from positive (upside) to negative (downside), and it considers that the POS is affected by various geological factors as well as upside and downside determined by NPV expectation curves. Finally, the application of exit options and pruning of the tree is performed automatically when the expected outcome will be negative.

The new VOI method deployed in this paper could be further improved by:

- Replacing distance weighted correlation strengths for NPV
- Apply multiple distance weighted functions for underlying geological parameters (Bickel et al., 2008)
- Ensemble generation of geological reservoir characterization models for key subsurface properties affecting reservoir performance, and update such ensembles by progressively introducing new constraints for the ensemble generation and use updated ensemble generations in the remainder of the tree. The ensemble based techniques allow for more robust optimization of portfolio and VOI results, but are computationally very intensive requiring HPC computational power (Barros et al., 2016). Furthermore a-priori ensemble models for reservoir characterization rely strongly on high quality (well) data, which works particularly well for VOI in reservoir management (Barros et al., 2016). It is beyond the scope of this paper to analyse the merits of such approaches.

Applying the improved VOI method to the case study of the Slochteren Formation in the Netherlands, clearly demonstrates that prospect portfolios with an initially low POS (ca. 50–60 %, such as at locations 1 to 4) benefit strongly from a play-based portfolio approach, capable of reducing the risk-reward ratio from 3 to 0.25 (Fig. 14). Thus, when applying the portfolio approach to other case studies, an initially low POS is preferred. When the spatial correlation between prospects is stronger (k-value lower) the learning effect is higher, which is associated with faster derisking. The applicability of a play-based portfolio approach is mainly beneficial for prospects with relatively low initial (marginal) POS. Such prospects benefit strongly from extra information (coming from e.g. geological analogues, studies, outcrops, research, seismic data, core measurements, etc.), not only for later projects in the same geological layer, but also in younger sequences. When a deeper aquifer is targeted, information can also be collected from shallower aquifers, which allows shallower targets to be de-risked at little extra cost. From the portfolio analysis it is also clear from the decision tree representation that VOI is largest for the information flowing at drilling the first prospect (Appendix B). Using such findings from the play-based portfolio analysis, targeted exploration drilling can be done to unlock resource potential by further reducing risk. For example, in 2022 a permit has been granted to conduct geothermal exploration research in (among others) the Slochteren Formation in Amstelland, the Netherlands (Janszen, 2022; Cariaga, 2023). Research drilling will be done by government-owned EBN (Energie Beheer Nederland). Information from such drillings could provide valuable information for the geothermal energy potential of the Slochteren Formation in nearby areas such as our study area in Flevoland. This will further contribute to the reduction of risks of the identified portfolios.

We emphasize that the NPV evaluation and underlying subsurface property mapping for the case study is subject to further improvement, prior to exploration drilling:

- The results in the SW part of Flevoland are uncertain due to the low data density in this area. More data (e.g., wells, seismic) would be beneficial in this area as this would decrease the geological uncertainty.
- Fault behaviours and their effect on the burial anomaly needs further study, as these have a strong impact on the performance of geothermal operations.
- Current techno-economic parameters and engineering assumptions on doublet design are largely based on generalizations in ThermoGIS, and need to be further tailored to the study area. Consequently, the resulting NPV values in this study serve as indicative values. In particular, the business case does not take into account differences and additional costs of developing heat transport to existing or the construction of new heat networks.

In this study we focused on the benefits of the portfolio approach in terms of VOI of prospect drilling, which is demonstrated by applying the portfolio approach to the Slochteren case study in The Netherlands. However, a play-based portfolio approach can have various other complementary benefits including: continuous improvement by integral project development, cost reductions through synergy, efficiency and standardization, optimization of surface heat demand- and infrastructure, possibility of increased research and development, and innovations, and financing and investment benefits (Van Wees et al., 2020). These benefits have not been explicitly evaluated in the NPV of follow-up projects in this method and case study, but can be considered to some degree as part of the POS correlation strength effect. When applying the portfolio approach to other case studies these benefits can be manifested. Regional studies are required to define potential areas for future application of the play based portfolio approach. Such studies could be executed in regions with large geological uncertainty resulting in low to moderate POS (significantly lower than 90 %), yet sufficient (expected) spatial correlation in geothermal reservoir properties is present for the VOI in a portfolio of potential prospects. This requires conceptual models for spatial correlation in reservoir properties or sufficient analogue data and/or geological models in adjacent areas, believed to be representative for the studied region. The high spatial correlation adopted in this study is supported by the wealth of subsurface data and many successful runner-up doublet systems in adjacent areas, which is exceptional and cannot be interpreted as universally applicable to any region. Therefore, in order for other regions to benefit from the updated VOI analysis (taking spatial geological correlation into account) a minimum in data density is needed. In various basins such as the Paris Basin or the South German Molasse Basin this is the case, in which the properties of geothermal plays have been studied in much detail (Moeck et al., 2019; Seithel et al., 2019; Renaud et al., 2024). In these areas our spatially correlation controlled VOI method might be very beneficial in order to determine the geothermal potential in local areas with lower data density. By knowing the pairwise distance between prospects for these areas, the strength of the correlation coefficient can be calculated by using eq. A9 (Appendix A).

## 6. Conclusions

In this paper, we presented an improved method for geothermal play-based portfolio analysis. It considers the effect of imperfect information (where correlation strength is expected as a function of distance). It uses continuous values for the NPV marked as an expectation curve for NPV from positive (upside) to negative (downside). It considers that POS is affected by various geological factors as well as the upside and downside determined by NPV expectation curves. Finally, the application of exit options and pruning of the tree is performed automatically under the right conditions. This updated method is mathematically more advanced and robust (honouring spatial geological correlation between prospects) compared to the former VOI method in which simple positive correlation is assumed for follow-up prospects.

The added value of a play-based portfolio approach was demonstrated, based on the Slochteren geothermal play in the central Netherlands in a realistic case study. The property maps of this region demonstrate relatively good reservoir potential in the W-, NW- and N-part of Flevoland, whereas the SW part of Flevoland (around Almere) indicates relatively low reservoir potential. A priori-NPV calculations were made with the cost-engineering model which has been used for ThermoGIS, a national geothermal resource information system for the Netherlands, complemented with an extension for an industrial heat pump, and tailored to the heat supply for district heating in this region.

The updated VOI method was used to evaluate the VOI for realistic prospect portfolios in five targeted locations, constrained in size by the prognosed heat demand in the region, and based on spatially correlated geological factors assumed to directly influence the economic probability of success (POS) based on the corresponding NPV expectation curve. The case study successfully demonstrated the added value of a play-based portfolio for relatively low marginal POS conditions (POS ca. 50–60 %). For a stand-alone approach, the prognosed reward ranges between 0 and 2 million € with an associated risk of 3 to 6 million €, depending on the development location. This is an unfavourably high risk-reward ratio of ca. 3 which hampers further development. For the portfolio approach, the risk-reward ratio is lowered significantly to ca. 0.25 and could be further reduced by financial incentives to de-risk the first prospect.

The application of the portfolio approach demonstrates that information acquired in the first prospects and used for decisions in follow-up projects within the same geologic play contributes significantly to the business case. It indicates that the development of the remaining prospects after the success of the first prospect is positive, even with high initial risk. A stronger correlation strength between prospects is associated with a stronger risk-reduction. This method thereby increases the probability of the play being developed, the number of successfully developed projects, and the average profitability of the project. This way geothermal exploration could be accelerated.

## CRediT authorship contribution statement

**Marianne van Unen:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Logan Brunner:** Writing – review & editing, Software, Conceptualization. **Hans Veldkamp:** Writing – review & editing, Methodology. **Ruben Keijzer:** Software. **Jan Diederik van Wees:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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## Appendix A. Event tree probabilities for a portfolio of correlated prospects

### A.1. General VOI analysis

In a play-based portfolio method the marginal probability of each individual prospect being successful in a portfolio with multiple prospects, can be represented by its POS:

$$P(E_1) = P(E_2) = \ldots = P(E_n) = POS \tag{A.1}$$

Prospects are denoted $E_i$, where $i$ is an index from 1 to the maximum number of explorative prospects $N_{prospects}$ in the portfolio. The prospects are drilled in sequence, starting from 1 to $N_{prospects}$.

Subsequently, the probability of a successive prospect succeeding in the tree assuming a positive correlation, can be defined as:

$$\mathrm{P}(E_2|\ E_1) = \min(POS + \Delta p, 1) \tag{A.2}$$

A case where the previous prospect succeeded is defined by:

$$\mathrm{P}(E_2|\ \overline{E_1}) = \max(POS - r\Delta p, 0) \tag{A.3}$$

$\Delta p$ marks the enhancement of probability. The factor r is needed to preserve the marginal probability of the second prospect, which can be derived from:

$$P(E_2) = POS = \mathrm{P}(E_2|\ E_1)\ P(E_1) + P(E_2|\ \overline{E_1})\ P(\overline{E_1}) = (POS + \Delta p)\ POS + (POS - r\Delta p)\ (1 - POS) \tag{A.4}$$

This implies by dividing eq. A5 over (1-POS):

$$r = \frac{POS}{1 - POS} \tag{A5}$$

In the case of a sequence of three prospects the joint probability outcomes for success in $E_{3,}$:

$$P(E_{3,}E_2, E_1) = P(E_3|E_2, E_1)\ P(E_2\ |E_1)P(E_1) = P_v(2,0)P_v(1,0)\ POS \tag{A.6a}$$

$$P(E_{3,}E_2, \overline{E_1}) = P(E_3|E_2, \overline{E_1})\ P(E_2\ |\overline{E}_1)P(\overline{E}_1) = P_v(1,1)P_v(0,1)(1 - POS) \tag{A.6b}$$

$$P(E_{3,}\overline{E_2}, E_1) = P(E_{3,}|\overline{E_2}, E_1)\ P(\overline{E_2}\ |E_1)P(E_1) = P_v(1,1)P_v(0,1)(1 - POS) \tag{A.6c}$$

$$P(E_{3,}\overline{E_2}, \overline{E_1}) = P(E_{3,}|\overline{E_2}, \overline{E_1})\ P(\overline{E}_2\ |\overline{E}_1)P(\overline{E}_1) = P_v(0,2)(1 - P_v(0,1)\ )\ (1 - POS) \tag{A.6d}$$

Chance of success is calculated where $\mathrm{E}_n$ is given and $\overline{E}_n$ is not given.

Which sums to marginal probability POS with

$$P_v(n_{succes}, n_{failure}) = POS + (n_{succes} - r\, n_{failure})\Delta p \tag{A.7}$$

Where $P_v$ is the POS of the decision tree branch (conditional probability) corresponding to the number $n_{succes}$ of positive and the number $n_{failure}$ of negative outcomes of prospects previously drilled. The $P_v(n_{succes}, n_{failure})$ can be effectively adopted in a decision tree representation for the portfolio as have been implemented in Van Wees et al., 2020. It follows from recursion that for any size of portfolio of prospects the marginal probability POS is preserved if r is in accordance with eq. A.5.

### *A.2. Updated VOI method*

In the previous section the portfolio assumes a constant marginal POS for prospects and a correlation effect that is uniform in the portfolio. More computationally intensive techniques facilitate variation of the marginal POS of the prospects and learning effects across the prospects.

To this end, the methods of Bickel et al. (2008) and Van Wees et al. (2008) define conditional probabilities though a pairwise (spatial) correlation strength of a particular geological factor. This method can be used for multiple geological factors each having different spatial correlation characteristics. This is denoted through a correlation coefficient $\rho_{E_iE_j}$ bearing the following relationship with pairwise conditional and marginal probabilities between prospects i and j:

$$\rho_{E_iE_j} = \frac{P(E_i)\left(P(E_j|E_i) - P(E_j)\right)}{\sqrt{P(E_i)(1 - P(E_i))P(E_j)(1 - P(E_j))}} \tag{A.8}$$

The strength of the correlation coefficient $\rho_{E_iE_j}$ can be conveniently represented as an inverse exponential function of pairwise distance $d_{ij}$ between prospects in km (Van Wees et al., 2008):

$$\rho_{E_iE_j} = e^{-k\, d_{ij}} \tag{A.9}$$

In the method of Bickel et al. (2008) the joint probabilities for the occurrence of geological factors in multiple prospects (either true or false), are represented as $p(\boldsymbol{w}) = (w_1, w_2, .., w_n)$, where $p$ is the vector of probabilities and $w$ is a state vector of outcomes of the (set of) geological factor(s), of the corresponding branch in the tree (for each w value either 0 or 1). The pairwise correlation coefficients result in a set of constraints for the joint probabilities which are solved by a Lagrange multiplier method (Bickel et al., 2008). These can be solved independently for multiple geological factors, treating the factors as independent. Spatial correlations for geological factors such as permeability may be known from well log data or other sources.

The joint probabilities of the state vector can be used to populate conditional probabilities of branches in a decision tree similar to equation eq. A.7:

$$P_v(\mathbf{w}_{succes/failures}, \mathrm{w}_{branch}) = p(\mathbf{w}_{succes/failures}, \mathrm{w}_{branch})/p(\mathbf{w}_{succes/failures}) \tag{A.10}$$

Where $p(\mathbf{w}_{succes/failures})$ is the joint probability of encountering the state vector of outcomes in the decision tree preceding the branch outcome ($\mathrm{w}_{branch}$).

## Appendix B. Resulting decision trees.

The decision tree analysis enables a quantification of the NPV and risks associated with prospect development. The decision trees give a quantified comparison between a play based portfolio approach and a stand-alone approach.

The decision trees show the following aspects:

- Green branches show a successful project
- Red branches show a unsuccessful project
- k-value is the spatial correlation. The lower the k-value the stronger the spatial correlation, associated with less prospects that need to be developed in order to reach success.

In general, all trees show that when having a stronger spatial correlation (lower k-value of 0.2) the successful projects (at 90 % or more) are reached at the second prospect (Fig. B.1). When adopting a higher k-value and therefore weaker spatial correlation only location 3, 4 and 5 reach successful projects of 90 % or more. These have longer decision trees (more prospects that need to be developed for success) associated with higher costs and risk, and less reward compared to a lower k-value.

Location 5 is not benefitting from a play-based portfolio analysis as the initial POS is sufficiently high to develop the portfolio. Thus, the decision trees of location 5 could be excluded from the study. However, we include the tree in order to demonstrate that a prospect with high initial POS is not preferred in terms of a play based portfolio approach and a stand-alone approach is preferred (see also Fig. 14).

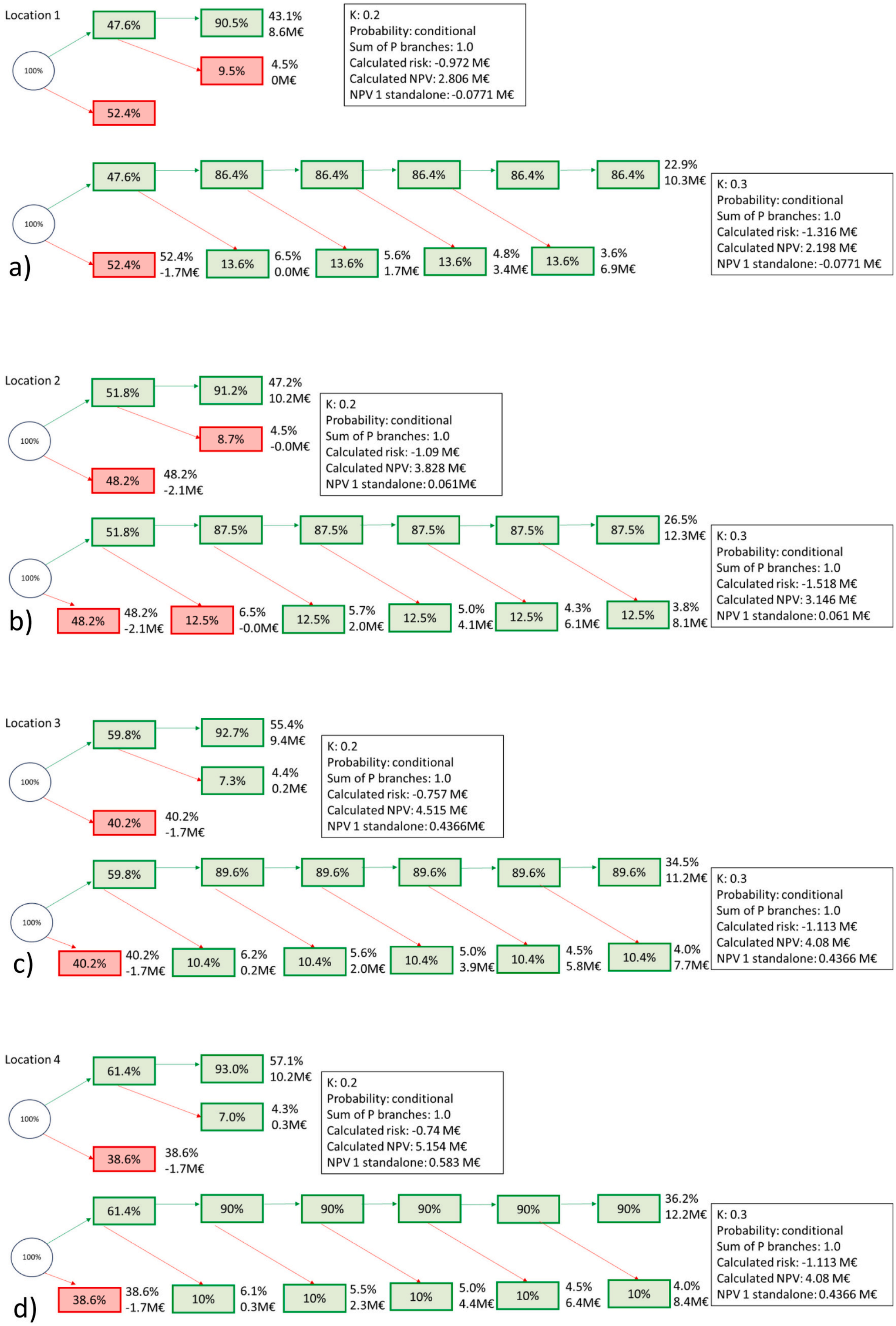


**Fig. B.1.** Decision trees for the portfolio of 5 prospects associated with spatial correlations of k = 0.2 and k = 0.3 for each location. a) location 1, b) location 2, c) location 3, d) location 4 and e) location 5. When progressing deeper in the trees each positive outcome shows that the portfolio yields a progressive positive business case after the hurdle of the first prospect.

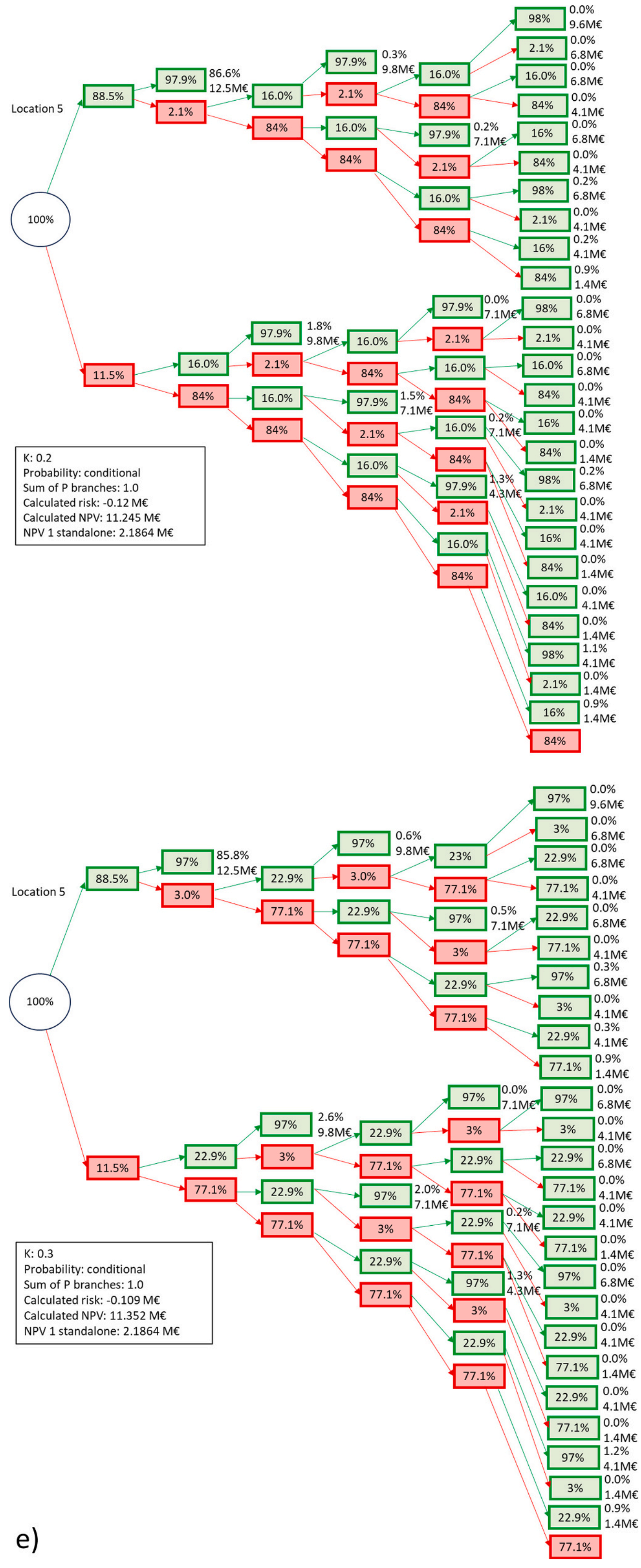


**Fig. B.1.** (*continued*).

## Data availability

The geothermal potential and property maps, necessary input for the VOI analysis, are available through www.thermogis.nl/thermogis-mapviewer.

The temperature used for establishing the geothermal potential maps is based on the Dutch 3D temperature model (source: www.thermogis.nl/en/temperature-model).

Property data for selected wells have been derived from www.nlog.nl/datacenter.

The stochastic technical performance calculations of the doublet, which serve as input to the NPV calculation, have been based on the most recent public domain version of DoubletCalc1D V1.5 (www.nlog.nl/tools).

Some economic input values used for the VOI analysis are standard default values derived from www.thermogis.nl/en/economic-model. However, not all details can be given on the values of the economic input parameters due to confidentiality reasons.

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