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Colophon

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Dutch Geothermal Research Agenda (Kennisagenda Aardwarmte)
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Well logging data: their value for the operator and for others

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Samenvatting

Boorgatmetingen (well logging) zijn niet alleen belangrijk voor de optimalisatie van de exploitatie van het geothermische reservoir, maar ook voor (toekomstige) exploratie van nabijgelegen geothermische projecten. Een boorgatmeting is echter kostbaar en brengt mogelijk risico's met zich mee. Daarom is het van belang om inzicht in de toepasbaarheid, bruikbaarheid, meerwaarde, risico's en kosten van de verschillende boorgatmetingen te krijgen. Dit overzicht is nodig om goed gefundeerde besluiten te nemen en de maximale opbrengst uit de putten te halen.

Dit onderzoek, uitgevoerd in het kader van de Kennisagenda Aardwarmte, geeft in een drietal deelonderzoeken een overzicht van de huidige stand van zaken met betrekking tot boorgatmetingen voor geothermie in Nederland.

Als eerste worden de verschillende argumenten om een boorgatmeting uit te voeren geïntroduceerd. De belangrijkste motieven om boorgatmetingen uit te voeren zijn: geologische toepassingen, 'drilling and completion' engineering, reservoir engineering en exploitatietoepassingen. Hiernaast wordt ook kort ingegaan op welke technieken beschikbaar zijn en waarvoor ze worden gebruikt. Onderscheid wordt gemaakt tussen 'logging while drilling' (LWD) en 'wireline logging', dat na het boren wordt uitgevoerd. Tenslotte wordt in dit hoofdstuk de huidige praktijk in de Duitse en Nederlanse geothermische industrie met betrekking tot boorgatmetingen onder de loep genomen. Hieruit blijkt dat in Duitsland historische putdata moeilijk te verkrijgen is, waardoor geothermische operators een relatief breed scala aan meettechnieken gebruiken. Aan de andere kant zijn Nederlands geothermische operators geneigd zo min mogelijk te meten, mogelijk gemotiveerd door het relatief grote aanbod aan publiek toegankelijke historische putdata én de extra kosten. Hiernaast blijkt uit de analyse van de Nederlandse situatie dat (minimale) drilling and completion boorgatmetingen en metingen voor exploitatietoepassingen meestal toegepast worden.

Het tweede deelonderzoek gaat in op de economie en risico's van boorgatmetingen. Naast deze twee onderwerpen wordt ook een korte 'Value-of-Information'-exercitie uitgevoerd. De kosten van een boorgatmeting hangen sterk af van de gebruikte techniek, de lengte van de meting - wordt alleen het reservoir of het gehele puttraject gemeten? - en de motivatie voor de boorgatmeting. Wanneer gebruikt gemaakt wordt van LWD zijn de kosten van een boorgatmeting 12 tot 14 k€ per dag, terwijl bij een wireline boorgatmeting de kosten variëren tussen de 25 en 150 k€. Op basis van deze schattingen is geconcludeerd dat een

wireline boorgatmeting meestal voordeliger is dan een LWD-operatie. Uit interviews komt naar voren dat de risico's verbonden aan boorgatmetingen goed beheerst worden, helaas zijn geen openbare statistieken beschikbaar waarmee dit gevalideerd kan worden. Hiernaast bevatten sommige instrumenten een radioactieve bron, wat op zichzelf een potentieel risico is. De VoI-exercitie illustreert dat, ondanks de extra kosten, het uitvoeren van (de juiste) boorgatmetingen zinvol is. Bijvoorbeeld bij productieproblemen in de put. Op basis van de eerste twee deelonderzoeken wordt aanbevolen om voor een geothermisch project een 'formatie-evaluatie' boorgatmeting uit te voeren om de geologische condities en reservoirkarakteristieken te bepalen.

In het derde en laatste deelonderzoek wordt een 'stakeholder analysis' uitgevoerd en ingegaan op recente ontwikkelingen met betrekking tot boorgatmetingen in de geothermische industrie in Nederland. Uit de stakeholder analysis blijkt dat voor alle geïdentificeerde aandeelhouders (operators, overheid, adviseurs, boorbedrijven, investeerder, etc.) het belang van boorgatmetingen groot is, maar dat de kosten op dit moment volledig gedragen worden door de uitvoerende geothermische operators. Verder zijn de belangen van toekomstige geothermische operators slecht behartigd. Hiernaast heeft de overheid veel invloed, maar wordt deze (nog) niet benut. Aangezien het vergroten van de invloed in de besluitvorming rond boorgatmetingen voor een geothermisch project geld kost, zouden de aandeelhouders die daar belang bij hebben een fonds kunnen oprichten. Dit geldt met name voor de boorgatmetingen nodig voor geologische toepassingen en reservoir engineering. In ditzelfde hoofdstuk worden ook twee recente ontwikkelingen besproken. Ten eerste de houding van SODM, die aanstuurt op stringentere veiligheidsmaatregelen bij geothermieprojecten. Ondanks dat de geothermische industrie het niet eens is met de visie van SODM, is de verwachting dat deze discussie zal leiden tot een grotere interesse in boorgatmetingen bij geothermische projecten. De tweede vindt een geleidelijke verschuiving plaats van geothermische operators die één project beheren, naar operators die meerdere geothermische projecten ontwikkelen en beheren. Ook deze ontwikkeling zal naar verwachting leiden tot een toegenomen interesse in boorgatmetingen bij geothermische projecten.

Het is in het belang is van de gehele Nederlandse geothermische industrie om de producerende geothermische reservoirs beter te begrijpen. Het uitvoeren van de juiste boorgatmetingen is één van de manieren om dit doel te bereiken. De verschillende partijen actief in de geothermische industrie kunnen hier ieder op eigen wijze aan bijdragen. Het lijkt daarom logisch om, aangezien het in ieders belang is, de kosten van boorgatmetingen voor geologische toepassingen en reservoir engineering te verspreiden over de hele geothermische gemeenschap. Een andere mogelijkheid is dat de overheid dit afdwingt of organiseert in, bijvoorbeeld, het garantiefonds.

Summary

Well logging is not only important to optimize the exploitation of a geothermal reservoir, but equally important for the (future) exploration of nearby geothermal projects. However, a well log is costly, and increases the risks of the project. Therefore, it is necessary to understand the benefits, costs and risks of the available well logging tools, including their applicability in different situations. Based on this knowledge (future) operators can make informed decisions and improve the performance of the geothermal doublet.

This study is carried out in the Kennisagenda Aardwarmte program and consists of three sub-studies. Together they provide an insight in the current state of well logging for geothermal project in the Netherlands.

First, the different arguments to carry out well logging operations, being geological applications, drilling and completion engineering, reservoir engineering, and exploitation applications, are introduced. Additionally, the different well logging techniques available as well as their purpose, are shortly discussed. A distinction is made between logging while drilling (LWD) and wireline logging, which is performed after drilling. Finally, the differences between the German and Dutch current practices are investigated. From this comparison it is concluded that in Germany it is difficult to obtain historic well log information and as a result, the application of well logging is common and relatively complete. On the other hand, Dutch operators generally deploy the minimum required well logging, probably motivated by the publicly available historic well logging data and the extra costs associated to the logging operation. The analysis of the Dutch situation also shows that (a minimum of) well integrity measurements and measurements for exploitation purposes are normally carried out in geothermal projects.

The second study comprises the economics and risks of well logging. Additionally, a brief Value of Information analysis is carried out. The costs of a well log depend on the tools used, the length of the log – is only the reservoir or the entire well measured? – as well as the motivation for the well logging operation. When using LWD the estimated costs for a well log are between 12 and 14 k€ a day, while for wireline well logging the costs vary between 25 and 150 k€. Based on these estimates it is concluded that, in general, carrying

out a wireline operation is the more cost effective than LWD. Interviews conducted indicate that risks are well mitigation during well logging operations, however, as statistics are not (publicly) available, this is not validated. A potential risk is that some tools use a radioactive source. The VoI analysis shows that, despite the extra costs, sensibly carrying out well logging measurements is useful. For example when production problems are encountered. Based on the first two sub-studies, it is recommended for a geothermal project to carry out a formation evaluation well logging operation to determine the geological conditions and reservoir characteristics.

In the third sub-study a stakeholder analysis is carried out and some recent developments in the Dutch geothermal industry are discussed. The stakeholder analysis indicates that for all identified stakeholders (operators, government, consultants, drilling companies, investors, etc.), interest in well logging is high, but that the costs are entirely paid by the geothermal operator. Also, the interests of future geothermal operators are currently poorly accounted for. Although the influence of the government is significant, it is not (yet) utilized. Since increasing the influence on the decision-making process for well logging operations for a geothermal project costs money, the interested stakeholders could cover this bay erecting a fund. This is especially valid for those measurements necessary for geological applications and reservoir engineering. In this same chapter, two recent developments are discussed. First, the recent publications of SODM, which, although not recognized by the geothermal industry, are likely to increase to interest in well logging in the geothermal industry. Second, a gradual shift is taking place from single-project geothermal operators to multi-project geothermal operators. It is also expected that this development will increase the interest in well logging in geothermal industry.

It is in the interest of the entire Dutch geothermal industry to increase the understanding of the producing geothermal reservoirs. Sensibly carrying out well logging measurements is a method to achieve this goal. The various parties active in the geothermal industry can all contribute here individually and in their own way. Consequently, it is seems logical to share the costs of well logging for geological applications and reservoir engineering across the geothermal community. Another option is that the government enforces this in, for example, the existing guarantee fund.

1

Introduction

1.1 Problem definition

Well logging is highly valuable for optimal reservoir management and for future exploration. However, logging is costly and there are risks involved. Sometimes the acquired data is of great value for future operators or for the development of the geothermal reservoir as a whole. Contrarily, the risks and costs are often borne by the first geothermal project.

The lack of certain well logging data can result in a large difference between the p90 and p50 of the geothermal power for new projects in the surrounding area. This has a negative impact on the financial feasibility of new geothermal projects. For the optimal use of the heat present in a specific reservoir, as well as for the individual project good understanding of the subsurface is important. Therefore, it is necessary to understand the benefits, costs and risks of the available well logging tools, including their applicability in different situations. Not only for the project at hand, but also for future exploration of the reservoir or for evaluating future doublet interferences of different geothermal projects. Based on this knowledge (future) operators can make informed decisions and improve the use of 'their' reservoir.

1.2 Objectives of the project

The goal is to provide information on the optimal use of well logging in different geological situations. A sub-goal of this project is to increase understanding among the industry and authorities concerning benefits, costs and risks of the different logging methods in geothermal wells, so they can make the best informed decisions.

Furthermore, the result can be used by individual operators to decide on the logging-suite for one or both of their wells. Additionally, organizations like DAGO[1] can use the outcome to inform their members on the added value of well logging data, on well logging techniques, corresponding risks, and possibly start discussions on the sharing of costs and benefits of these data with existing and future operators. A possible future step is to use this report to establish well logging guidelines for the geothermal industry.

1.3 Plan of approach

Extensive logging literature and handbooks are available, though no specific research or literature on pro's-con's, costs, risks or an overview of considerations for logging in the geothermal industry is known. Therefore the following phases are defined:

[1] Dutch Association of Geothermal Operators (DAGO)

Phase 1 Create an technical overview of the well logging methods

In this first phase the focus is on the technology of well logging and the applications in Dutch geological conditions.

1. Defining the geological parameters and the Dutch geological conditions which can be investigated by well logging. The main focus is on Dutch sand- and limestone up to 3,500 m b.s.l.
2. An overview is presented on well logging techniques used in geothermal exploration and exploitation. Logging techniques are divided into open hole and cased hole logging, as well as into logging during drilling (LWD[2]) and logging after drilling (wireline logging). Measurements taken while drilling (MWD[3]) to control the drilling process and seismic logging are not included in this research.
3. An overview of technical experience in The Netherlands and Germany on well logging for geothermal projects.

Phase 2 Economical and risk analyses of well logging

In this phase a basic logging suite is defined and judged on economics, risks and benefits. The perspective in this phase is the operator.

1. Determining the 'basic logging suite': logging techniques that should be applied when drilling geothermal wells in The Netherlands. Based on approximations for a case study, the potential added value of a certain set of geothermal logging techniques is estimated.
2. An overview of the expected costs, risks and benefits of the applicable logging tools for the case study is given.

[2] Logging While Drilling (LWD)
[3] Measurements While Drilling (MWD)

Phase 3 Stakeholders analyses

In this phase the use of well logging as seen from the perspective of the different stakeholders is analyzed.

Who are the different stakeholders and what is their interest in well logging? Stakeholders are, for example, the operator of a geothermal system, (potential) nearby operators in the same reservoir, the Dutch geothermal industry, and the government, both local and national.

Phase 4 The future of well logging in the Dutch geothermal market

Using the input from the stakeholders discussion, recommendations are defined on how to share the costs, benefits and risks of well logging.

2

Overview of well logging techniques

2.1 Objectives of well logging

In order to have an economically feasible geothermal project, the investment into the geothermal system must be earned back during its lifetime. It is known that during a geothermal system its lifetime problems are encountered, such as, for example, scaling, corrosion, clogging, and thermal breakthrough. When any of these problems occur, the operator is required to solve them as quickly and adequately as possible. A sound understanding of the producing geothermal reservoir is therefore indispensable. Utilizing this knowledge, some of the problems can be avoided while for others mitigation measures can be applied.

Before drilling starts, an extensive geological research is carried out. The results of this research form the basis on which the well locations and well designs are determined. The well design determines which materials should be available before and during the drilling of the wells. Consequently, it is challenging to make rigorous changes to the well design on basis of well log information without significant delays and additional costs.

The information derived from well logging is (potentially) applied at all stages during development and operation of a geothermal system. In comparison to hydrocarbon practice, not all possible applications are equally useful.

Geological applications

During drilling, the information derived from well logging is used to validate the predicted depth of the penetrated zone tops and geothermal reservoir. Additionally, this information is used to correlate the geothermal well with the offset wells used to study the geothermal reservoir. This information can then be used to optimize the well design of the second well of the geothermal doublet.

Drilling and completion engineering applications

After the wells have been drilled and cased, the wells must be cleaned and the casings checked. Using well log information, the final well design and well cleaning program are updated to the local characteristics of the producing formation. Valuable well logging information at this stage is, for example, the presence and thickness of the mud cake, the exact location and depth of the producing (permeable) zones in the reservoir, the salinity and composition of the formation water, the formation water pressure, and the water temperature at reservoir depth.

Also important here are indications of overpressure (for the mud weight), determining cementing parameters based on borehole volume and condition as well as checking cement integrity.

Reservoir engineering

The predicted permeability and porosity of the geothermal reservoir can be validated by analyzing well logging data. This information is then used to determine the exact volume water volume present in the geothermal reservoir and model the temperature and pressure in the reservoir during the lifetime of the geothermal system.

Other useful reservoir engineering parameters which can be measured using well logging techniques are, for example, the orientation and magnitude of the local stress field, and geomechanical parameters.

Exploitation applications

Furthermore, to accurately and sensibly monitor the performance of the geothermal system, the initial state of the geothermal doublet must be determined. To this end a baseline survey is carried out and initial values such as, for example, the skin, are measured.

During operation, governmental regulations require regular well integrity control. Well logging tools such as a cement bond log and a casing log are commonly applied to check well integrity.

Benefits for the geothermal community

Besides the information that is not only useful for the geothermal operators, also future projects can benefit from well logging data. Correlation of geothermal reservoir characteristics between different geothermal fields will stimulate a steep learning curve and accommodate more cost-effective realization of (future) geothermal projects. In the case two geothermal projects are developed in the same geothermal reservoir at nearby locations, well logging and sharing knowledge will probably result in the most optimal geothermal field development, preventing thermal breakthrough between the two systems.

2.2 What is well logging?

Geophysical logging

The continuous recording of a geophysical parameter along a borehole produces a geophysical well log. The value of the measurement is plotted continuously against the depth (along hole) in the well.

The most appropriate name of this continuous depth-related record is a geophysical well log, conveniently shortened to well log or log. Because historically the first logs were measurements of electrical properties, a well log is often called an “electrical log”. However, the measurement are no longer simply electrical and as for data transmission a wireline is no longer need, the name “well log” is recommended (M. Rider 2002).

Some of the geophysical measurements can also be used to estimate geomechanical parameters (like Poisson’s ratio, Young’s modulus). These parameters are, for instance, used to determine the orientation and magnitude of the local stress field. The magnitude and orientation of the stress field is important in relation to the maximum allowable injection pressure and induced seismicity.

In Figure 1 an example of a wireline logging operation is shown.

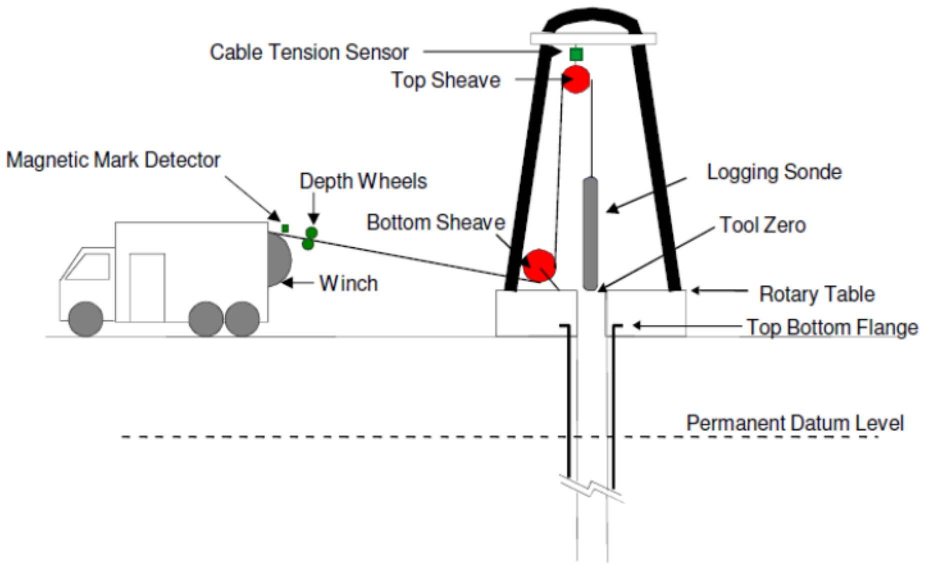


Figure 1 Example of a wireline logging operation. Shown are amongst others, the logging truck with the winch, the drilling rig, the logging sonde (or tool string) as well as the logged borehole .

Open and cased hole logging

A borehole logging operation can be carried out in an open or a cased hole. The motivation for cased hole logging is found in three categories, already discussed before (Section 2.1):

- Logging for formation evaluation and/or reservoir monitoring.
- Logging for production engineering
- Logging for well intervention or well integrity.

Open hole logging is solely used for formation evaluation, and can be divided into the following four categories, also discussed before (Section 2.1):

- Petrophysics
- Geology
- Geophysics
- Reservoir Engineering

These different categories are elaborated on in the following paragraphs.

Formation evaluation and reservoir monitoring

Formation evaluation is the term used in the hydrocarbon industry to determine the ability of a borehole to produce hydrocarbons. In geothermal formation evaluation is used to determine the ability of the drilled reservoir to produce geothermal fluids. This implies determining the ability of the geothermal reservoir to allow fluid flow by estimating its porosity and permeability as well as the depth and thickness of the reservoir and the vertical location of its producing layers.

Production engineering

For production engineering it is relevant to know the fluid movement and flow rates in and out of the reservoir, as well as accurate knowledge of fluid properties.

Well integrity

Besides geophysical parameters, the integrity of the well along its depth can be measured. Well integrity is an important aspect of every (geothermal) well at some stage during its lifetime. Consequently, the well integrity affects the overall performance of the well and the geothermal system.

The major difference between geophysical and well integrity logging is that the geophysical logging can also be carried out in an open hole, while the well integrity logging is always done in a cased hole.

In Table 1**Error! Reference source not found.** a short overview of the main purposes of the different logging methods is given.

Table 1 Logging methods and their purposes

Method	Purpose
Geophysical well logging and borehole imaging	Reservoir properties (porosity, permeability, …)
	Water quality (salinity, temperature, …)
	Lithology and geology
	Stress field (orientation, magnitude)
	Fracture detection
	Analysis of borehole stability
	Identification of breakouts[4]
Well integrity and production engineering	Cement bonding
	Thickness casing and liner (casing inspection)
	Fluid movements and flow rates

Wireline Logging (WL) and Logging While Drilling (LWD)

In the 1970's, a new approach to (geophysical) wireline logging (WL) was introduced in the form of logging while drilling (LWD) to avoid the removal of the drill string to be able to log in an open hole. This technique provides similar well information to conventional wireline logging but instead of sensors being lowered into the well, the sensors are integrated into the drill string and the measurements are made in real-time. This allows drilling engineers and geologists to quickly obtain information such as porosity, resistivity, hole direction and weight-on-bit. Theoretically, they can use this information to make immediate decisions about the future of the well and the direction of drilling (Tarab H. A. and et al. 2008).

A comparison between Wireline Logging (WL) and Logging While Drilling (LWD).

Both WL and LWD have their advantages and disadvantages. The main advantage of LWD is its avoidance of the time elapsed between drilling and completion of logs as well as all the associated consequences such as fluid invasion, time maneuvering, round trips, additional risk hole collapse. Another advantage of LWD is the possibility of profiling wells with raveling problems often preventing the operation of WL. Furthermore, as LWD delivers real time information about the borehole, directional control of a wellbore is possible. Also

[4] Breakouts are associated to irregularities in the borehole wall that are aligned with the minimum horizontal stress and appear where stresses around the wellbore exceed the compressive strength of the rock.

LWD deployment for logging in high angle or horizontal boreholes is considered a good option, especially during in-field development drilling. Because the tool string is located directly behind the drill bit, the zones are measured soon after they are drilled.

Consequently, it is easier to measure the uninvaded zone. Additionally, as the tool string passes the drilled zones a few times, the zones can be logged at various times for time-lapse evaluation.

A disadvantage of LWD is that the tool string is placed behind the drill bit and therefore more sensitive for disturbances induced by the drilling. Also, not all existing WL services are readily available for LWD, e.g. cement bond logs and other cased hole services, VSP[5] borehole seismic, and PVT[6]-quality fluid sampling.

The main advantage of WL is, as its services are only required from time to time, that its presence at the drill site is only necessary at specific moments. In contrast to most LWD tool strings, which come with a limited number of tool configurations, a WL tool string is job specific and only contains the necessary logging tools.

Based on the above, it is concluded that:

a) the number of tools in the WL tool string can be limited to what is necessary for the job, and,
b) the time WL service is required is short in comparison with LWD,

the service costs for a WL operation are often lower than those of a LWD operation for the same project. Consequently, despite the obvious advantages of LWD, it is not always the most logical option. Other important factors are the equipment logistics, such as, for example, handling and the space required by logging tools.

The (logging) results obtained by both methods (WL and LWD) are comparable while the costs associated with each method are variable (Bastos A. R. G, n.d.).

[5] Vertical Seismic Profiling
[6] Pressure/Volume/Temperature

2.3 Overview logging techniques

In Table 2 a selection of logging tools is given, as are the main purposes to use these tools. Details on how these tools work can be found in the various standard works on well logging methodology.

Table 2 Summary of the most important well logging methods and their application. Adjusted from Rider, 2002

Logging tool \ Uses	Lithology	Stratigraphy correlation	Depositional environment	Fracture identification	Over-pressure identification	Porosity	Permeability	Shale volume	Formation water salinity	Seismic
Caliper		-		-			-			
SP (*obsolete?*)		-	-				-	+	*	
Resistivity	-	-	-		+	+	-		-	
Gamma ray	+	-	-	-				+		
Sonic	+	-	-	*	+	*	-	+		*
Density	+	-	-	+	-	*	-	+		*
Neutron	+	-	-			*	-	+		
NMR[7]	+	-	-			*	+	+		
Fluid testing and sampling					*		*		*	
Borehole imaging[8]			*	*						

- essentially qualitative use

+ semi-quantitative and quantitative uses

* strictly quantitative

2.4 Experiences in the Netherlands

Besides running the required logs, almost no additional log operations are carried out in Dutch geothermal wells. In general, the reason is that these additional logs are costly and that the benefits for the geothermal operator are unclear. The idea is that the benefits of the additional logs do not outweigh the additional costs for the geothermal operator.

[7] Nuclar Magnetic Resonance
[8] Both acoustic and micro-resistivity imagers

The logs that are carried out are mostly LWD and are used for identification and correlation purposes. In most cases only a gamma ray and caliper are used. The measurements are compared with the ones expected and based on the observations made, the reservoir is identified.

In a few geothermal wells additional logs were carried out. In Koekoekspolder, for example, a NMR was carried out. This log was deployed to measure the quality (permeability) of a shallower reservoir (Brussel Zand Formation). Furthermore, leak off tests are regularly carried out.

2.4.1 Operator experiences in The Netherlands

For this research, four geothermal operators were approached for an interview. Ultimately, three operators were actually interviewed. All operators were asked the following questions:

A. Before drilling, was performing well logging measurements considered? Is so, was the logging to be conducted while drilling or as wireline? Why?
B. Which subsurface of well parameters were the aim of the well logging?
C. What were the estimated costs of the well logging operation?
D. Was the well logging performed as Logging While Drilling or Wireline logging?
E. Did any unforeseen events occur due to the logging which increased the costs of the project?
F. Did the results of the well log measurements had a significant added value to the success of the project of drilled well.
G. Was it during drilling decided to conduct well logging, despite it was decided earlier not to log. If so, why?

Results

A. All operators interviewed, considered well logging before drilling. In all cases, a LWD gamma ray was measured. Additionally, two operators indicated that they measured a casing log and cement bond log in order to establish the base case situation for well integrity. One operator carried out a temperature measurement of the reservoir, while another conducted a wireline operation (gamma ray, sonic, density, neutron porosity, and nmr) for geothermal formation evaluation.
B. Gamma ray logs were measured to determine lithology correlation at depth, and establish whether the geothermal reservoir had been reached. Cement bond and casing logs are required by the mining authorities for well integrity. The operator

who carried out the formation evaluation did so to determine porosity and permeability of the geothermal reservoir.

C. Costs of the logging operations carried out are In the range k€110 to k€160.
D. Gamma ray LWD, casing log and cement bond log wireline, formation evaluation open hole wireline.
E. No unforeseen events did occur during the logging. One operator indicated that they are concerned for the radioactive methods utilized by of some of the formation evaluation tools. Nevertheless, they consider to run a formation evaluation logging operation for their next project. One operator insured the tools string for loss in hole during open hole wireline operation for approximately €4000.
F. Most logs were measured for monitoring purposes, in these cases value-for-money is not relevant. As the results of the formation evaluation did not match to the well test carried out, this particular operator did not considered the formation evaluation logging results as adding value to his project. One operator suggested that the formulation of a clear standard by DAGO (Dutch Association Geothermal Operators) is desired.

After the drilling was completed, well tests were carried out. Besides a visual inspection using a camera to identify corrosion problems, no additional, unscheduled well measurements were carried out.

2.5 Geothermal well logging operations in the Netherlands

On 21st July 2017, the 12 geothermal projects published on NLOG.nl[9], drilled a total 35 geothermal wells. The well logging operations carried out for these projects are listed in Table 3. It is important to realize that Dutch law prescribes raw well log data to be made publicly available 5 years after the measurements are carried out. This implies that all projects where measurements are stated as “unknown”, are not yet available in the public domain.

From Table 3 it is concluded that 6 out of 12 projects at least performed a LWD Gamma Ray measurement for depth correlation. As this is good practice and required by the mining authorities, it is expected that all project measured at least a gamma ray and a cement bond log, although the cement bond log might not always be published at NLOG.nl.

[9] www.NLOG.nl is the portal, maintained by TNO, were all publicly available subsurface information, with respect to the Mining Law, of the Netherlands can be accessed.

At least three project, CAL-GT, HON-GT and KKP-GT, carried out a wireline logging operation for formation evaluation. It is known that EBN participated in the CAL-GT project, but it is not yet known which well logs were run in the wells.

For well integrity purposes, cement bond and casing logs are ran for most projects as well.

Table 3 Overview of the measurements carried out in geothermal projects (NLOG.nl; 21-7-2017)

Geothermal field code	Number of wells	Spud Year	Measurements
BRI-GT	2	2015	Not publicly available
CAL-GT	5	2012	Gamma ray, sonic, image, cement evaluation, resistivity, and NMR log, cores
HAG-GT	2	2010	Gamma ray (LWD)
HEK-GT	2	2013	Unknown
HON-GT	2	2011	Gamma Ray, Density, Sonic, PEF (Wireline); cement bond and casing log
KHL-GT	2	2016	Not publicly available
KKP-GT	2	2011	NMR, Gamma Ray, Density, Neutron Porosity, Sonic (Wireline); cement bond log
LIR-GT	2	2014	Unknown
MDM-GT	6	2013	In well MDM-GT-5: gamma ray, sonic, density and neutron logs (all wireline, open hole).
PLD-GT	2	2016	Unknown
PNA-GT	4	2010	Gamma Ray (LWD); cement bond log
VDB-GT	4	2007	Gamma Ray (LWD); cement bond and casing log

2.6 Experiences In Germany

Well logging within the geothermal industry in Germany can be divided into well logging for technical purposes and well logging for the geoscientific investigation of the reservoir. While the information gathered by technical well logs is limited to the particular well, geoscientific well logs are used to characterize the local reservoir system and can thus have a high value during future exploration and exploitation of the field, both for the operator of the geothermal license field and for the operators of neighboring fields. Technical logs, on the other hand, are often mandatory due to legislation and are used to prove the safety and integrity of a newly drilled well.

2.6.1 Technical well logs

Execution of the German Mining Code is controlled by the individual federal states, resulting in different prescriptions for the use of well logs existing there.

A common practice is to perform logs that verify the integrity of the well by performing cement evaluation and casing inspection.

The German Mining Code strictly regulates the thermohydraulic influence of geothermal wells to be limited to the borders of the geothermal license field. An accurate knowledge of the well path is therefore mandatory. A deviation survey is therefore an integral part of all newly drilled wells. They become even more important with the advancement of deviated drilling within the geothermal industry.

Other

Nowadays a common practice is to perform an optical imaging survey using downhole cameras. They provide a high-resolution color image of the well and allow for the comparison of the condition of the well before and after maintenance work. The condition of the gravel pack is often analyzed using GG density logs.

Geoscientific well logs

The use of specific geoscientific well logs depends on the local geology and on the exploitation approach that results from the local geology.

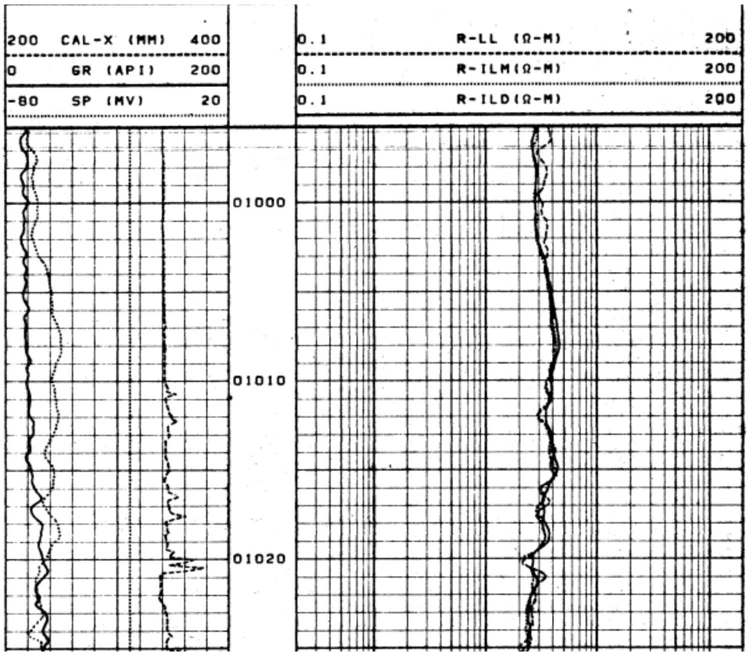
The value of old well logging data

The main geothermal regions of Germany were intensively investigated and drilled by the oil and gas industry during the 20th century. Basic data of all wells drilled in Germany are accessible through the “Geologische Landesämter” (Geological Survey of the federal state concerned). These data include coordinates of the well head, final depth and final geological formation of the well, ownership of the well and the available well logging data. These data can be inquired at the Federal State Geological Surveys. One can then inquire the well owner and purchase the data for exploration purposes. Generally, the well logging data are not publicly available.

During the pre-feasibility phase of geothermal projects, data from these existing wells are an important source for the characterization of the potential reservoir system. Geoscientific well logs are important for the operator of a geothermal license field and for the operators of neighbouring fields.

Typically, old well log data is only available on paper sections. Accordingly, they have to be scanned and digitized in order to further process the data.

Figure 2
Example of a typical old well log; CAL (caliper), GR (gammy-ray) and SP (spontaneous potential) on the left; LL (laterolog) and DIL (deep induction log) on the right; old well logs have to be scanned and digitized.



2.6.2 The value of geoscientific well logs for the operator

Gamma-ray (GR) data can be used to correlate geological formations over the extent of a license field, thus improving the geological model of an reservoir system. The new GR data can be combined with GR data from nearby existing wells.

Pressure-Temperature (PT) logs are used during well testing after drilling of the well. They can be run with internal memory or as a wireline log with real time data recording. If more than one well is available in a geothermal field, PT logs are run in the neighbouring wells to estimate permeability values of the reservoir system as well as the mutual influence of the wells on the reservoir system.

Sonic logs and density logs can be used for estimation of reservoir parameters such as porosity and lithology. But they can also be used for the preparation of synthetic seismograms that are a valuable tool for the creation of seismic velocity models in a well tie. They are useful directly after drilling but also during future exploration studies since they can greatly enhance seismic depth models.

Modern borehole image well logs can be used to infer the direction of the maximum and minimum horizontal stress. The analysis of the present-day stress field is now a standard tool in the characterization of a geothermal reservoir and faults zones are preferred targets due to enhanced permeability values associated with their damage zones. Permeability is even higher along faults that have an angle of 20 – 45° with respect to the maximum horizontal stress and can thus be targets in future drillings into a geothermal field. For stress field analyses, density logs also play an important role since they are used for estimation of the vertical stress, S_V (Zoback 2008).

Well logging dependent on local geology

Permeability of geothermal reservoir systems can either be porosity controlled (e.g., porous sandstones in the North German Basin) or fracture controlled (e.g., fractured carbonate rocks in the Bavarian Molasse Basin). The choice of geoscientific well logs to be conducted depends on the type of reservoir system. In the case of porous sandstones, logs that are valuable for porosity estimation are favored. In fractured carbonate systems, fault zones investigated by seismic surveys are a preferred target which makes logs that are useful for seismic velocity models more important.

At what stage well logging is performed?

Compared to the oil and gas industry, geothermal energy still yields relatively small profits. This is reflected in a high importance of economic feasibility of the performed well logging. For this reason, well logging is almost exclusively performed after drilling of the wells. Well logging prior to drilling during the exploration phase would require the drilling of exploration wells, which is too expensive in most circumstances. Logging during exploitation is rarely done and is limited to periods of well maintenance. Typical well logs at this stage are VSP surveys that serve as a basis for future seismic measurements in the area.

Well logging data of existing wells, however, play an important role during the exploration for geothermal resources .

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Wireline versus measurement while drilling

Due to its high costs, measurement while drilling (MWD) is not performed in the German geothermal industry. Well logs are almost exclusively run as wireline logs. In the case of extreme borehole deviations (> 45°), logging tools are often attached to the drill pipe.

Most common logs

The most common well logs that are conducted in almost every geothermal project in Germany are:

- **Technical logs** (e.g. caliper, deviation survey, USIT): most of them are mandatory due to legislation.
- **GR** log as a tool for depth correlation, often used in conjunction with other logging devices.
- **Downhole temperature and flow meter** logs to measure the reservoir's condition.
- **Pressure-Temperature (PT) logs** during well testing.
- **Other geoscientific well logs** based on the local geology, present knowledge on the local reservoir system, future development plans (e.g., sonic and density logs for future seismic measurements) and economic considerations.
-

2.6.3 Economics and risks

Specific risks during well logging

Since the majority of geoscientific well logs are open hole devices, long open hole intervals have to be maintained for logging purposes. The risks associated with long open hole sections on well stability have to be taken into account when planning well logging activities which will limit the time available for the completion of the well logging operations. Long open hole sections are also a risk for casing installation and cementation of the well. As a result, the final well logging program will always be a compromise between a reduction of the well risks and a thorough investigation of the geothermal reservoir system.

A specific risk associated with well logging is the possibility of losing equipment in the well (LIH: lost in hole). While LIH events are only rare individual cases, almost everyone involved in drilling and well logging has experiences with LIH. However, in Germany there aren't any reliable statistics available on the frequency of LIH events.

2.6.4 Typical pricing in Germany

Pricing depends highly on market conditions (thus variable over time) and on the type of log. Typically, the total sum comprises a base price plus mobilization fee plus a price per meter. Most logs are performed using multi-tool devices where several logs can be measured in one single run. This can reduce both time and costs of the logging operations. Typical prices in Germany are:

Base price:	3,000 – 15,000 €
Mobilization:	2,500 – 25,000 €
Logging per meter:	3 – 80 €

The lower end of the pricing range is occupied by single, standard logs (e.g., well deviation). Single but more sophisticated logs (e.g., sonic logs) are in the medium price range and the highest prices are charged for multi-tool devices.

2.7 Conclusions

When comparing Dutch and German practices it can be concluded that the access to legacy well logging data for exploration purposes is significantly easier in the Netherlands. On the other hand, the lack of difficult to access, legacy data motivates the geothermal operators in Germany to deploy a wider range of well logging methods.

In both the Netherlands and Germany, the risks associated with well logging are sufficiently mitigated.

3

Economics and risk-analysis

3.1 Economics

To obtain an indication of the various options for running a logging operation, three logging companies[10] were asked to provide ball-park (cost) numbers for, as wells as feedback of, the following options:

- cased hole formation evaluation (wireline);
- open hole formation evaluation using LWD;
- open hole NMR using LWD;
- open hole formation evaluation using wireline;
- open hole NMR using wireline.

A typical formation evaluation logging operation comprises gamma ray, resistivity (laterolog and/or induction log), sonic, density, and neutron porosity logging tools. See Table 2 for the main applications of these techniques.

Other specifications are a 1,500 to 2,500 meter deep well. Furthermore the objectives of the logging measurements are 1) the determination of the porosity and permeability of the producing reservoir, 2) identification of the producing zones in the reservoir, 3) formation water quality and composition, and 4) formation water temperature, 5) pressure, and 6) magnitude and orientation of the stress field in the formation.

Responses

In general, it is not recommended to carry out a formation evaluation in a cased hole. Measurements are heavily influenced by the cement quality, borehole condition and the casing which shall shield a direct measurement of formation parameters. Furthermore, too many casing corrections are necessary to obtain a reliable evaluation. Although sonic, density and neutron are possible, costs are significantly higher compared to measurements carried out in an open hole.

The estimated costs of the open hole logging measurements are listed in Table 4. As mentioned before, wireline logging if generally less costly than LWD. Let's consider a 100 day long drilling operation at a rig rate of €12,000,-/day. Having LWD formation evaluation tools available the entire time will cost €1,200,000,-. When running a formation evaluation using wireline of the entire well assuming four sections and five days of logging, the logging operation will cost €210,000,- This is significantly lower in comparison with the LWD logging costs.

[10] Baker-Hughes, Halliburton and Schlumberger

Table 4
Ball-park numbers for logging operations for geothermal wells.

Option	Estimated logging costs
Formation evaluation using LWD	k€12-14/day
NMR using LWD	k€12-14/day
Formation evaluation using wireline	k€25 (formation evaluation of zone of interest only) to k€150 (formation evaluation of entire well, including well integrity.)
NMR using wireline	k€45 to k€75

Based on our inquiry, some other recommendations came to the fore:

- To maximize the results of the measurements, running wireline formation evaluation and NMR is suggested. With this combination all parameters of interest are measured. Depending on the length of interval measured, the costs will be in the range k€60-k€200.
- After completion temperature and flowmeter surveys are suggested (~k€15).
- Costs for a baseline survey providing details on the quality of the cementation and wall thickness are estimated at 35 to 40 k€.

3.2 Risk-analysis

A potential problem is that some of the logging tools are running a radioactive source. Solutions to minimize the risk of this aspect is splitting the tool string in two separate tool strings or estimating source-less porosity by combining resistivity, sonic and NMR. This risk mainly effects the measurements made for geological and reservoir engineering purposes.

Other risks, such as tools lost in hole or damaging of the bore hole wall, are well covered by the precautions and risk mitigation approaches the logging companies apply before logging. Based on the responses of the operators interviewed our interviews and the experiences in Germany, it is stated that risks associated with well logging are well controlled.

The operator of the geothermal well drilled is responsible for the consequences of the risks induced by the well logging survey. Although the risk of a tool lost in hole is very small, losing the tool is too costly for geothermal operators. To mitigate these risks, an insurance can be taken out via the service company. This is a new trend, specific for the geothermal industry.

3.3 Value of Information

Because the acquisition of additional data is costly, the question is if the additional data is worth the extra costs. To determine the value of the information (the data) a statistical approach has been developed by the oil and gas industry. This so-called Value of Information (VoI) analysis can also be applied on geothermal systems.

To be able to carry out a VoI analysis, the geological parameters that affect the performance of the geothermal system, for example by evaluating the predicted geothermal power, are defined first. Following, the financial consequences of a lower than predicted geothermal power are calculated. Finally, mitigation measures, their costs and their possible success for improving the (predicted) geothermal power are determined.

Next, after the additional data and their acquisition costs are included into the model, a similar analysis is carried out. The additional data make it possible to efficiently remove the cause and effect of the decreased geothermal power. In this case, more efficient means a higher probability of success. This higher probability of success indicates that acquiring the additional data are worth the extra costs.

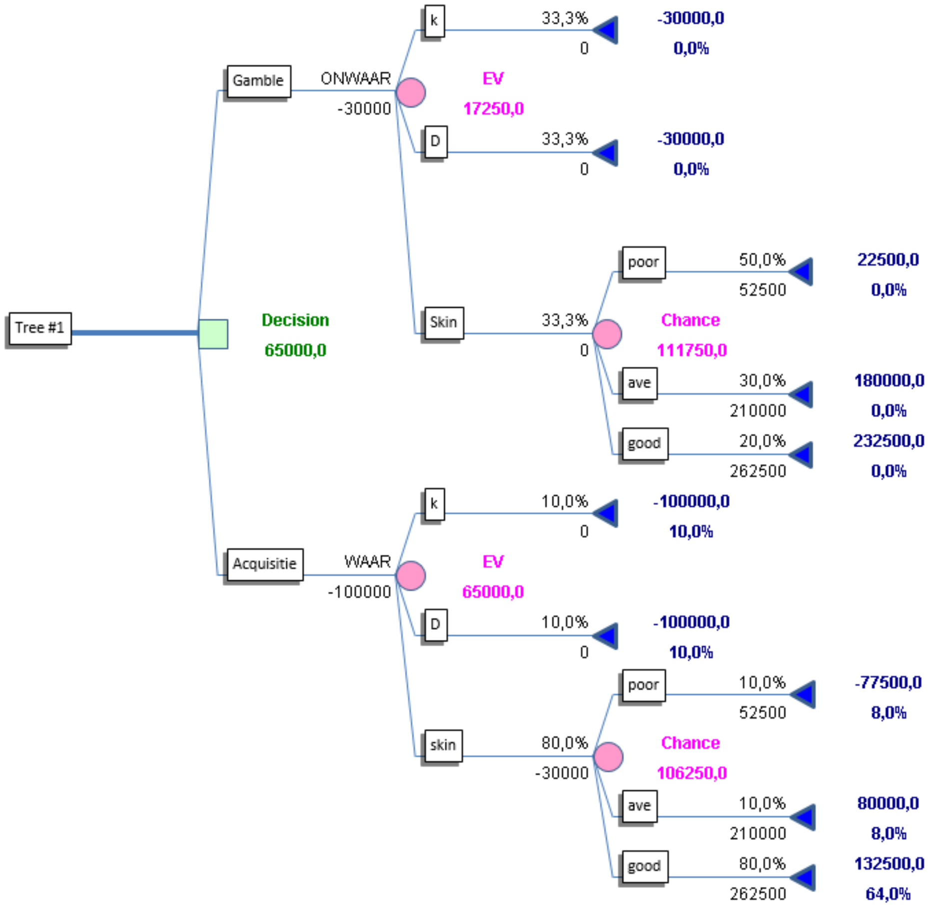
In Figure 3, an example of a VoI analysis is given. In this case, the geothermal power of a system is lower than expected. The reason is unclear, but three possible causes are defined:

1) a lower than expected permeability,
2) a lower than expected thickness, or
3) a skin.

Due to the lack of data it is not possible to determine the exact cause of the decrease in geothermal power. The likelihood of each cause is therefore equal. In general, an acid job is carried out when the productivity of a well is too low. In this example, the acid job will only be effective in 33.3% of the causes. Because the type and location of the skin are not accurately known, the success rate of the job is low. The costs of the acid job are estimated at € 30.000,-. When this approach is chosen, the expected financial gain of the project is € 17.250. The gain is calculated by assuming the skin causes an additional pressure difference of 5 bar, which results in additional electricity costs of € 262.500,- (in 30 years). The additional pressure difference caused by the skin is removed by the acid job.

In the branch in Figure 3 where the data acquisition is chosen, the expected financial gain is € 65.000 while the additional costs for the acquisition are € 100.000,-. Because in this branch the acid job can be carried out more efficiently and the chance of a negative case is completely removed, and consequently a higher expected value is achieved.

Figure 3
Example of a VoI analysis. EV is Expected Value, k is permeability, D is thickness.



This example illustrates that in some circumstances additional data acquisition for a single geothermal system operator are useful, even when considering the extra costs.

Similar VoI analyses can be carried out for, for example, the long term operation of a single geothermal system or the development of several adjacent geothermal systems in the same geothermal reservoir.

4

Stakeholder analysis

4.1 Introduction

For this stakeholder analysis, guidelines provided by the Dutch state are used. According to their description a stakeholder analysis results in an overview of the stakeholders who directly have a role in the decision making process of a (geothermal) project and those without a direct role, but who can influence the project. A stakeholder analysis is carried out to be able to involve the relevant parties and persons at the right moment in the planning of the project.

4.2 Stakeholder analysis

In this analysis, an inventory is made of the parties involved in a geothermal project and how they can cooperate.

Influence of stakeholders

As mentioned before, stakeholders involved in a geothermal project are divided into primary stakeholders, with much influence on decisions, and secondary, tertiary, etc., stakeholders, having less and less influence on decisions. In Table 5 below, the stakeholders are listed and sorted from "high" to "little" influence. In practice, more stakeholders are present in a geothermal project. However, for this study, a selection is made of the shareholders for whom well logging is considered to be relevant. A short description of the identified stakeholders follows below.

Table 5
Division of the direct and indirect stakeholders of a geothermal project

Influence	Rank	Stakeholder
High	1	Single Geothermal Operator Multiple Geothermal Operator
	3	National government (supervision and inspection) Insurance companies
	5	National government (funding)
	6	DAGO & Platform Geothermie
	7	Drilling company Service companies Investors (external) Geothermal consultants
Little	11	Universitities and research institutes Adjacent geothermal operator

Single Geothermal Operator

A single geothermal operator is typically a greenhouse owner, or a cooperation of greenhouse owner, interested providing energy for their greenhouses. They typically develop one or two geothermal system from a single location and are not interested in the lateral characteristics of the geothermal reservoir. They are satisfied with sufficient flow to meet their energy demands.

Multiple Geothermal Operator

A multiple geothermal operator has the ambition to develop and operate several geothermal systems. The number of this type of geothermal operators is currently increasing. They tend to be more interested in the lateral characteristics of a geothermal reservoir and the optimization of the geothermal production. It is expected that knowledge will increase as more project are developed.

National government (supervision and inspection)

Exploration and exploitation licenses are granted by the ministry of economic affairs. To this end they are supported by SODM, supervising drilling operations in the subsurface. Consequently, the national government has a significant interest in safety and environment issues during drilling and operation of a geothermal system, in the financial viability of a project as well in broader topics such as limiting the effects of climate change.

Insurance companies

Not producing sufficient flow is often insured by insured. Hence, limiting risks and uncertainties is crucial for insurance companies. A good understanding of the producing reservoir prior to drilling and during production contributes significantly to limiting the uncertainties.

National government (funding)

The national government runs a guarantee fund which can be compared to an insurance and provides a subsidy on basis of the probability distribution of the predicted geothermal power prior to drilling. The subsidy depends on the actual power produced in relation to this probability distribution. The more knowledge of a geothermal reservoir prior to drilling, the narrower and more accurate the probability distribution of the geothermal power. The more knowledge of a geothermal reservoir after drilling, the higher the geothermal power produced from a geothermal system.

Dutch Association of Geothermal Operators (DAGO) and Platform Geothermie

The two branch organizations benefit from a flourishing geothermal market. It is in their interest that future geothermal projects are successfully drilled and operated. Knowledge sharing is beneficial for these two organizations.

Drilling companies

The wells of a geothermal systems are drilled by drilling companies. They have in interest in bringing the right material and instruments to run a smooth and safe operation. Prior knowledge of the subsurface as wells as continuous measurements during drilling are crucial for ensuring those objectives.

Service companies

Service companies carry out well logging operations. Their interest is obvious.

Investors (external)

External investors have a limited influence in the project, but have significant interest in a good understanding of the reservoir to limit their risks.

Geothermal consultants

More and better data from the subsurface implies that geothermal consultants are able to provide better advice.

Universities and research institutes

Science will benefit from more and better data of the subsurface. On the other hand will the geothermal industry benefit from an increase understanding of the subsurface as acquired by research.

Adjacent geothermal operators

A current or future geothermal operator located in the close vicinity of a geothermal system has two interests in acquiring the knowledge of the subsurface. First, it is undesirable that the adjacent systems interfere. Second, prior to drilling a future geothermal operator is interested in understanding to geothermal reservoir to be drilled as good as possible.

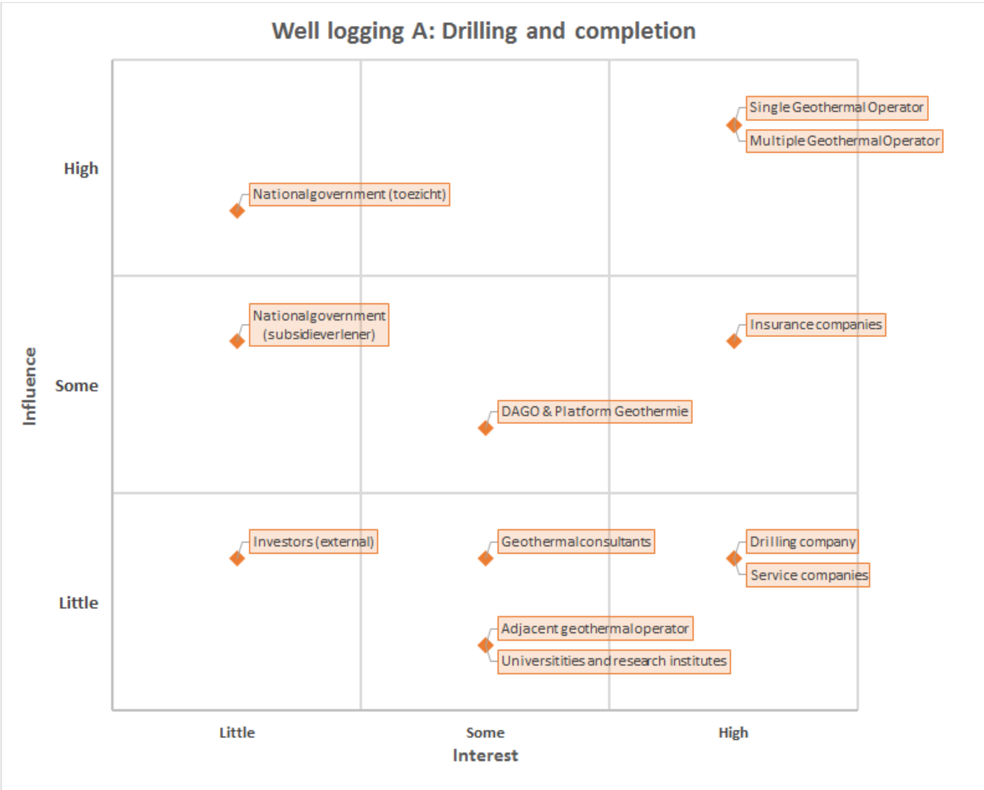
Stakeholders matrices

Based on the well logging types as discussed in Section 2.2, five types of well logging operations are defined. These types are:
Well logging A: Drilling and completion (Geology and water properties by logging).
Well logging B: Reservoir engineering (A + Reservoir properties and geomechanical properties).
Well logging C: Exploitation (A and/or B + recurrent monitoring measurements)
Well logging D: Well integrity (part of A and C)
Well testing T: Temperature and water sampling (part of B and C).
For each stakeholder, the interest in the well logging type is defined and plotted against their influence. The resulting interest versus influence plots are shown in Figure 4, Figure 5, and Figure 6. As well logging D is required by the government and of direct interest to the operator, no stakeholder matrix is presented for well integrity well logging. As well testing for temperature and water sampling is not considered in this study, no stakeholder matrix is presented.

From these three figures, it is concluded that currently the geothermal operator is the sole stakeholder who takes the important decisions. Generally, more generic stakeholders, such as, science, DAGO, and the geothermal industry, have a high interest, but little influence.

Figure 4 shows that well logging for drilling and completion is mainly of interest to the geothermal operator and insurance companies. Consequently, running a well logging for drilling and completion purposes is expected to be carried out in most geothermal wells.

Figure 4 Stakeholder matrix for well logging A.



From Figure 5 it is concluded that most stakeholders have a high interest in well logging for reservoir engineering purposes. However, at the current state of affairs only the geothermal operator has the influence to make this decisions. Additionally the government has some instruments at its availability to enforce influence. Nevertheless, It is desired that this influence is increased significantly.

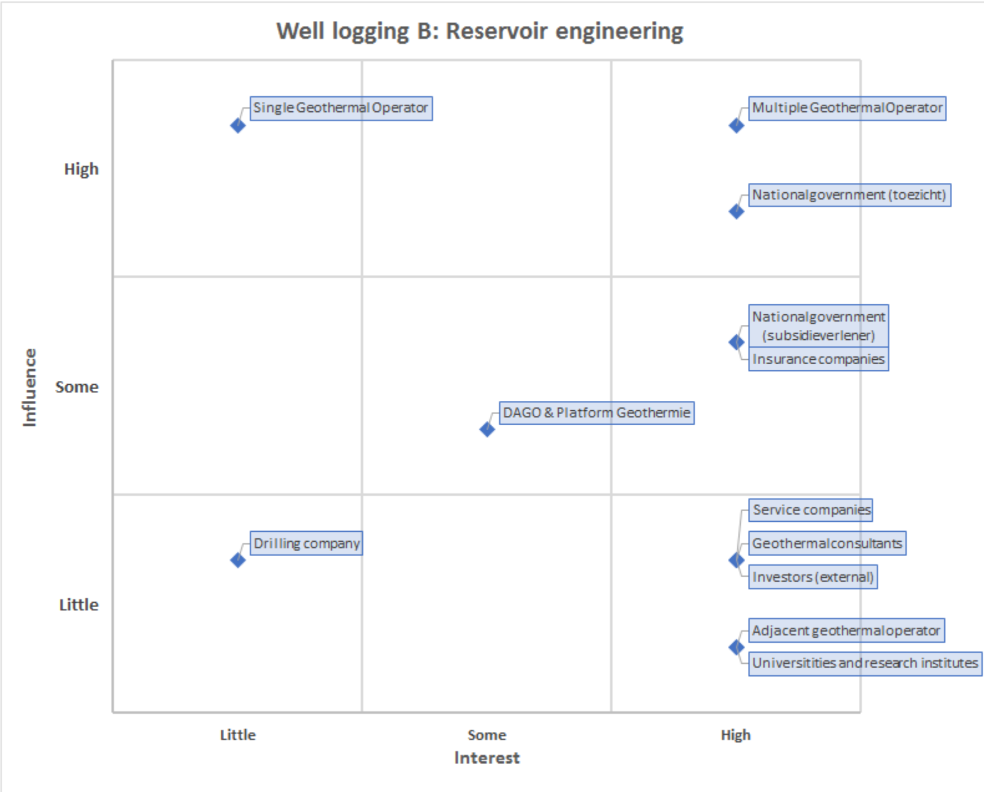


Figure 5 Stakeholder matrix for well logging B.

Figure 6 illustrates that logging for exploitation purposes is in the interest of the geothermal operator. Consequrently, all geothermal operators run recurrent monitoring logs.

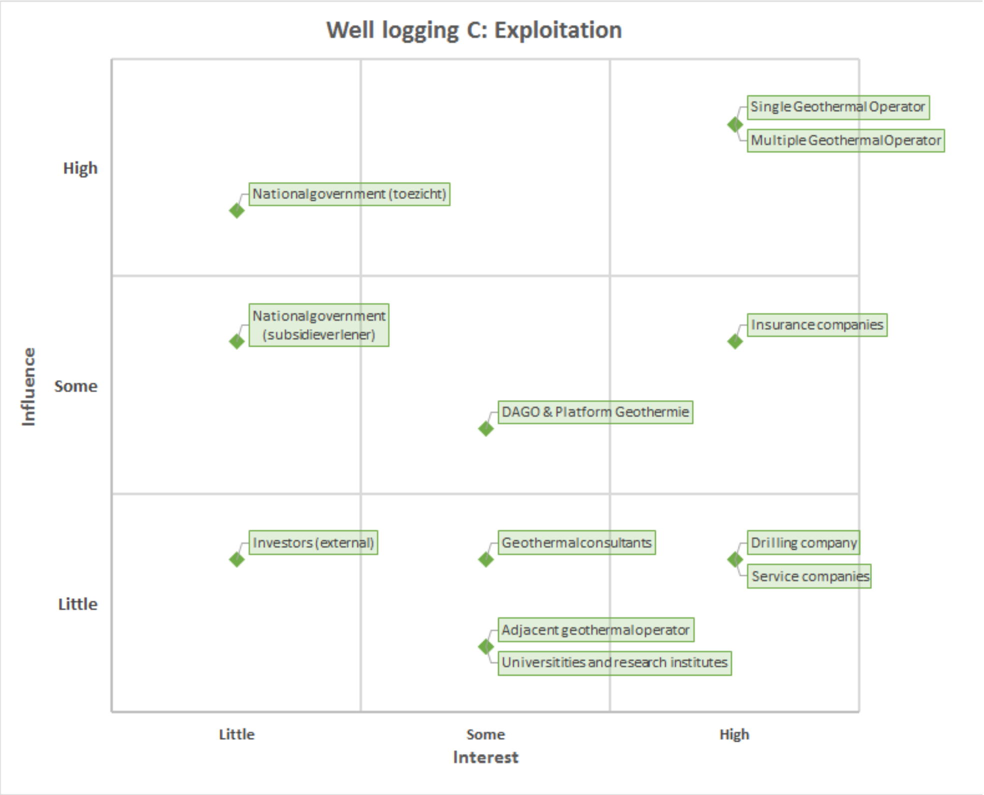


Figure 6 Stakeholder matrix for well logging C.

4.3 Recent developments

Two recent developments in the geothermal market, the contours of which are accounted for the in the analyses, will potentially shake up this stakeholder analysis.

First, the recently published vision on the geothermal market by SODM (see e.g.: https://www.sodm.nl/onderwerpen/aardwarmte/documenten/publicaties/2017/07/21/de-nederlandse-ondergrond-is-op-dit-moment-een-jungle) addresses the, according to SODM, poor safety measures in the geothermal sector. Based on the reactions of the branch organizations DAGO and Platform Geothermie, the industry disagrees with the statements of SODM, and states that cooperation and knowledge sharing between different geothermal operators is improving. It is expected that this development will increase the incentive to perform more (well logging) measurements in a geothermal well.

Second, were most geothermal operators are currently individual or cooperating greenhouse owners, currently municipalities, industry and energy companies are becoming the main players. As the generally tend to simultaneously develop several geothermal projects in the same region or reservoir, performing more complete well logging operations is expected.

4.4 Conclusions

From the stakeholder analysis carried out in this research it is concluded that interest in well logging is high among the stakeholders. On the other hand, the influence is often little.

The interests of future operators are currently poorly accounted for. This should be improved to secure the future of the geothermal market as it is desirable that the high confidence in the technique is maintained.

The influence of the government is significant, but not fully utilized.

It is stated that influence has a price. It is suggested that the government and/or branch organization such as DAGO and Platform Geothermie erect a fund to partly cover well logging cost. Especially for those necessary for reservoir engineering and geological applications.

5

Conclusions

From the Chapters above it is concluded that:

- Within the scope of this study, well logging is deployed for four reasons:

    1. Geological applications
    2. Drilling and completion applications
    3. Reservoir engineering applications
    4. Exploitation applications.

- Differences between geothermal practice in Germany and the Netherlands can be found in the availability of well logging data. Data availability in Germany is limited which results in a high motivation to carry out extensive well logging operations during the development of a geothermal project. On the other hand, as data availability in the Netherlands is generally good, the motivation to carry out well logging measurements is limited to what is required by regulations.

- Based on the cost estimates provided by selected well logging service companies, running wireline open hole measurements is the most cost effective.

- Drilling and completions application and exploitation logs are normally (partly) measured in a geothermal well.

- It is recommended to run a formation evaluation tool string setup to measure the geological conditions and reservoir characteristics.

- Risks associated to well logging operations are normally mitigated by careful preparation and/or taking out an insurance. Numbers are not available, but interviews indicate that damages or unexpected delay as a result of well logging is very limited.

- The Value of Information analysis showed that the costs of measuring additional data are justified when production problems in the well are encountered.

- The stakeholder analysis showed that although interest in well logging is generally high, the influence of important stakeholders is often (too) limited or not fully utilized. This is explained by the fact that currently only the operator is paying for the well logging.

- It is expected that recent development, both at a regulatory level and in the geothermal industry, will increase in the interest in well logging services during geothermal projects.

5.1 Recommendations

It is in the interested of all stakeholders active in the geothermal industry to elevate the probability of success of a geothermal project. One method to achieve this is to sensibly deploy well logging tools. To develop the geothermal industry as a whole the main focus should be on achieving a better understanding of the producing geothermal reservoirs in terms of reservoir properties and characteristics. Target areas, specified for different stakeholders, are:

1. *Individual operator.* Detailed knowledge of the properties (porosity, permeability, lithification) of the producing reservoir. Using this knowledge, the well completion can be optimized and potential production problems (e.g. fines) can be effectively mitigated. To this end, it is recommended to carry out a formation evaluation logging operation for at least the first production (or exploration) well in a new geothermal project.
2. *Individual operator.* Resistivity for presence of hydrocarbons.
3. *Multiple geothermal operator/Geothermal region.* Regionally (several projects in the same reservoir within the same area) detailed knowledge of reservoir properties improves reservoir engineering and limits the chance of thermal and hydraulic interference between projects.
4. *Multiple geothermal operator/Geothermal region.* Furthermore, in many cases, the applied time-depth model for the seismic inversion is of limited quality. In case the whole well is logged with a density and sonic log and a check-shot survey is carried out, the time-depth model is improved and predicted top reservoir depth (for new projects) is expected to be significantly improved, leading to a better estimate of drilling costs. Note that this motivation for logging is not covered in detail in this study.
5. *Dutch geothermal industry.* Increased knowledge of the producing geothermal reservoirs in the Dutch subsurface will decrease the uncertainty in the reservoir properties at a specific location. This influences the uncertainty of the predicted geothermal power for, for example, a SDE+ or RNES application. In other words, the difference between p50 and p90 is expected to become smaller.

As stated before, one of the reasons the deployment of well logging services in geothermal wells is limited is that currently the operator is paying. As interest in the results from well logging data extends beyond the interests of a single geothermal project, is seems logical that the costs of well logging measurements for geological and reservoir engineering applications are shared by the Dutch geothermal community.

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Appendix 1

Tool	Curve Name		LWD	Openhole	Cased-hole	What is measured?	Wat is it used for?
Gamma ray	GR		Yes	Yes	Yes	Natural radioactivity	Lithology, shale content, depositional environment, depth control
Sonic	DTC	Compressional-wave sonic	Yes	Yes	Yes	interval transit time through a formation	Porosity estimation, fracture and lithology determination and correlation Pore pressure determination, rock strength calculations, borehole stability analysis, time-to-depth seimic correlation
	DTS	Shear-wave sonic	Yes	Yes	Yes		
Resistivity	ML	Micro-log	Yes	Yes		Electrical resistivity	identify geological attributes (thin beds, dip, faults and fractures), condition of the borehole stress and rock mechanics around the borehole, assist in porosity determination, formation fluid
	MLL	Micro-laterolog					
	MSFL	Micro-spherically focused log					
	LL	Laterolog					
	LLs	Shallow laterolog					
	LLd	Deep laterolog					
	ILm	Medium induction log					
	ILd	Deep induction log					
Spontaneous potential	SP					Natural electrical potential	Lithology, shale content, formation water resistivity, permeability
Density	DENS	Density	Yes	Yes		Bulk density	Porosity, reservoir structure, well placement, time-to-depth seismic correlation, overpressure, lithology
Neutron	PHIN	Neutron porosity	Yes	Yes	Yes	Neutron absorption and slowing down of neutrons	Formation fluid-filled porosity
Nuclear magnetic resonance			Yes	Yes		Nuclear magnetic resonance of hydrogen	Fluid identification, indication of permeability, matrix-independent total porosity
Pore pressure			Yes	Yes		Direct pore pressure measurements	Formation evaluation, permeability indication, reservoir connectivity, optimal mud weight, anticipate on pressure changes, wellbore stability, reduction formation damage
Temperature			Yes	Yes			
Inclination			Yes	Yes			
Caliper	CAL	Simple caliper	Yes	Yes		borehole size and shape	quality control of logs and boreholes in general
		4-arm caliper					stress regime from breakout analysis