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A brief stock take of the deep geothermal projects in Bavaria, Germany (2018)

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ABSTRACT

In the last decades, the number of geothermal heat and power installations worldwide increased and the trend seems to continue. In Germany, three regions qualify for the installation of deep hydrothermal wells: the Upper Rhine graben, the north German Basin and the south German Molasse Basin. 26 deep geothermal projects have been realized in the south German Molasse Basin between 1998 and March 2018. In this paper, we provide an analysis of the current status of those southern German deep geothermal projects. The existing 26 hydrothermal geothermal projects have been evaluated in an empirical approach with respect to drilling success and other related parameters.

We find that a differentiation should be made between projects that are designed for heat and those that are designed for power production. Naturally, power projects aim at more ambitious target reservoirs at greater depths and require relatively high yields. This causes quite elaborated and rather long (sub-)horizontal drilling paths within the reservoir rock formation.

Based on the available data the success rate for heat projects including sidetracks and deepenings is 100%. For power projects the success rate is 75%. Analysis show that thus far there are two reasons that lead to unsuccessful projects in Bavaria: insufficient yields and for one project the natural gas content. Overall three projects were unsuccessful, which were all power projects and situated in the deeper southern part of the Molasse Basin. Regarding the drilling success rate, our study shows that the success rate of first-try boreholes for heat projects is with 94% three times higher than for power projects with 32%. The probability of encountering low yields or technical drilling problems increases beyond 3000 mTVD from 4% to 49%. Apart from exploration risks, higher thermal water temperatures that are naturally associated with power projects and higher yields are more likely to produce scaling and cause more damage to below and above ground facilities than lower temperature thermal waters that are sufficient for heat production. Analysis show an overall average drilling rate of 43 m/d. Comparing heat and power projects, heat projects show a slightly higher drilling rate with 47 m/d compared to 39 m/d for power projects.

Observed induced microseismicity occurred for both power and heat projects, mainly at the reinjection well locations. Overall eight microseismic events with magnitudes between M_L = 2,0 and 2,5 have been observed at three locations thus far.

Power projects are more ambitious than heat projects and awareness should be raised for the associated uncertainties. However, as power production from geothermal resources especially in combination with heat production remains an important pillar for any energy conversion scenario, significant improvements in all associated technological and reservoir related sectors need to be made in order to reduce the uncertainties described in this paper.

1. INTRODUCTION

Between 1998 and March 2018, 26 deep geothermal projects have been realized in the south German Molasse Basin in Bavaria, Germany (Figure 1). 21 are operating, two projects have been drilled and associated plants are currently in the planning or construction phase and three projects were unsuccessful (BVG, status March 2018). All of these projects are hydrothermal projects, which tap into the deep carbonate groundwater aquifer of the south German Molasse Basin, with a thickness of about 400 to 600 m (Meyer & Schmidt-Kaler 1996). Out of the 26 projects, 14 are heat projects used for district heating and 12 are power or combined power/heat projects. Further projects are in the pipeline and are soon being drilled or finalizing their planning stage.

The total installed deep geothermal energy in Bavaria is 295,9 MWtherm (Germany: 315,4 MWtherm) and 33,8 MWel (Germany: 34,8 MWel) according to BVG March 2018.

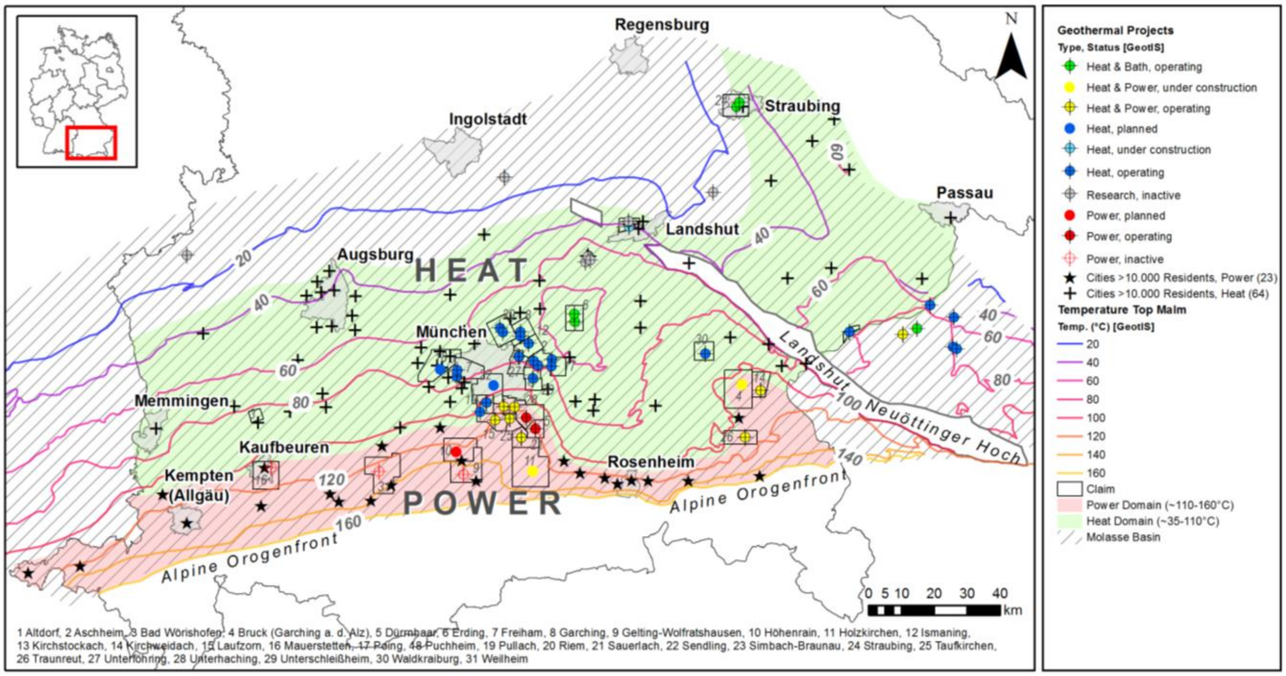


Figure 1: Locations of deep geothermal boreholes and projects in Bavaria along with heat (green) and power (red) domains based on the Top Malm temperatures and the existing geothermal projects.

To deliver a brief stock take and give indications of success rates and conditions of the 26 realized projects, several aspects of the project lifecycle were analyzed. The analyzed data was then grouped into heat and power projects, to be able to compare the two technologies. Definitions of heat and power projects in the context of this study are given below:

- Heat projects: defined as projects used for district heating or a combination of district heating and balneology; thermal water temperatures of up to approximately 110°C (110°C was chosen as the hottest heat project reaches thermal water temperatures of 109°C), and
- Power projects: defined as projects used to solely generate electricity or projects that combine heat and power generation; thermal water temperatures above approximately 110°C.

Projects solely used for balneological purposes are mentioned in some sections below to get some comparisons (e.g. Bad Wörrishofen). However, the balneological projects were not used for analyses in this study as they differ significantly regarding yields and design.

Success of deep geothermal projects depends on different factors during the lifetime of a project:

(1) Favorable geological conditions - a convenient setting for a certain deep geothermal technology, in this case: hydrothermal. This is given in the south German Molasse Basin in Bavaria, with a deep aquifer system, the Malm (Upper Jurassic), and thermal water temperatures of about 30 to 160°C. (2) Approval by authorities and acceptance in the community - a project can fail before it has started. Communities can form initiatives to stop projects if their concerns are not addressed appropriately. (3) Drilling and completing a functional well. (4) Reaching the targeted temperatures and flow rates. (5) Economical continuity with sufficient customers to consume the produced heat and/or power. (6) Expected or unexpected issues during the operation or caused by the operation, e.g. scalings, gas, problems in plant or seismic events. Such issues can have an economic or social effect on the project and in the worst case can lead to the termination of the operation.

This study focuses on factors (3), (4) and (6). Used data is based on the geothermal information system GeotIS (Agemar, 2014), the oil and gas database KW-FIS and the Energieatlas Bavaria.

2. ANALYSED PARAMETERS

2.1 Drilling Success

The majority of deep geothermal projects in Bavaria consist of two wells, one production and one injection well, a so-called doublet. Rarer configurations are double doublets – two production and two injection wells or triplets – two production and one injection well. One project is about to construct a triple doublet.

Ideally, drilling a geothermal well is successful on the first try. Success in this case means reaching the targeted temperatures, a minimum flow rate for a given drawdown and having a functional borehole construction. The targets are defined by the economic concept of the project. However, due to unsolvable technical problems during drilling operations (e.g. broken casing or a stuck drill string) or not reaching the required temperatures or yields, some wells are unsuccessful (lost hole). In a recent case, another reason arose for the first time, which led to an unsuccessful borehole: natural gas. This project in the south of the Molasse Basin first seemed to be unsuccessful due to insufficient yields. After additional hydraulic testing the yields seemed to be sufficient, however, the natural gas content of the aquifer could not be controlled and the project was subsequently stopped and the borehole closed (Taaleri, 9 May 2018). To save wells that had technical problems or did not reach the required temperatures or yields and still ensure a positive outcome of the project, the operator can either deepen the well or drill a sidetrack (acidizing has not been mentioned here as it is considered by the authors to be a standard method to increase productivity of a borehole). Some other technical options are being discussed and research projects are being carried out, but the mentioned techniques are until now the main solutions used in practice. Non-drilling ways to save a project are for example to redesign the plant to accommodate the encountered yields and temperatures, to change the economic concept or to change the end user, where instead of delivering electricity one can use the energy to heat for example a fish farm or a greenhouse. If sidetracks or deepenings do not achieve the necessary temperatures and yields and the concept of the project cannot be adjusted economically, the project is abandoned and unsuccessful.

What is the success rate of drilling a deep geothermal well in Bavaria? In Bavaria, 75 boreholes were drilled for the 26 deep geothermal projects (status March 2018): 53 first-try wells, 17 sidetracks and 5 deepenings. Figure 1 illustrates the 75 boreholes as a “drilling family tree”, grouped into heat and power projects. This family tree shows the chronology and relationship between the first-try wells and the associated sidetracks or deepenings. As an example: the well on the right hand side of the heat projects in Figure 1 was not successful on the first try (red). In a second try, the well was deepened (marked as D) but unsuccessful again (red). On the third try a sidetrack (marked S) was drilled which lead to a successful well (green).

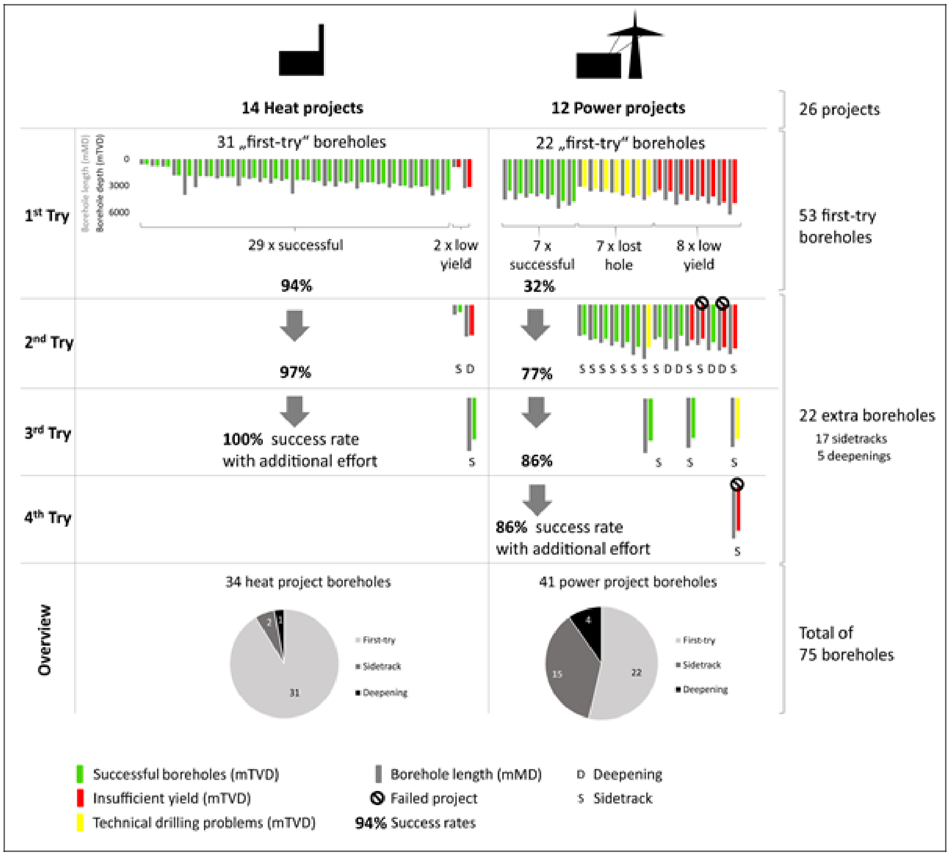
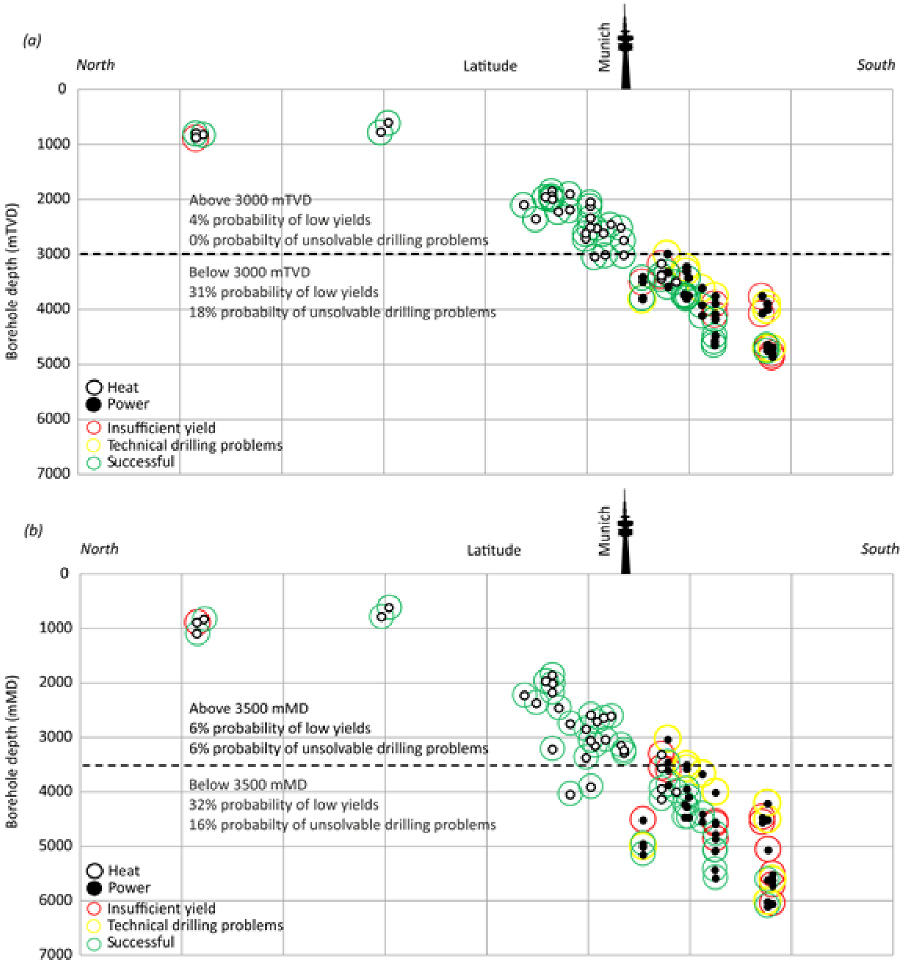


Figure 2: Drilling success sequence of the 75 deep geothermal boreholes in Bavaria, grouped into heat and power projects. It shows chronologically if holes were successful on the first try or needed additional tries. It also shows the depth of each borehole as either meters drilled (mMD) in grey or total vertical depth (mTVD) in green, red or yellow.

As shown in Figure 2, success rates and the number of drilled sidetracks and deepenings differ between heat and power projects. The success rate of first-try boreholes for heat projects is three times higher than for power projects. Wells that were unsuccessful due to technical drilling problems (yellow bars in Figure 2) occurred for power projects only and not for heat projects. The total number of sidetracks and deepenings is 22, of which three were drilled for heat projects and 19 for power projects. With additional effort, meaning drilling sidetracks or deepening the borehole, the success rate increased to 100% for heat projects whereas for power projects the final borehole success rate is 86%, with three boreholes and thus projects remaining unsuccessful (black crossed circles in Figure 2).

Figure 3 demonstrates the relationship between the drilled depth or length (mTVD and mMD respectively) and the success rate of a borehole. Unsuccessful low yielding wells and technical drilling problems occur more often beyond a depth of 3000 mTVD and 3500 mMD. Above 3000 mTVD 4% of the boreholes show low yields and 0% technical drilling problems. Below 3000 mTVD 31% of the boreholes show low yields and 18% technical drilling problems. The borehole depth and the number of meters drilled, especially when drilled at an angle seem to increase the risk of technical drilling problems (Brasser et al., 2014). Notably, all boreholes abandoned due to unsolvable drilling problems were drilled at an angle.



	Heat domain	Power (heat) domain
Thermal water temperature:	35-109°C, Ø 83°C	118-168°C, Ø 137°C
Borehole length:	610-4120 mMD, Ø 2663 mMD	3025-6084 mMD, Ø 4650 mMD
Borehole depth:	610-3500 mTVD, Ø 2280 mTVD	3000-4900 mTVD, Ø 4000 mTVD
Inclination:	12-90°	16-63°
Inclined section:	0-3950 m Ø 1470 m	945-4300 m Ø 2660 m
Yield:	30-100 l/s, Ø 74 l/s	50-145 l/s, Ø 112 l/s

Figure 3: Drilling success of projects in the Bavarian Molasse Basin in comparison to the total vertical borehole depth (mTVD) in graph (a) and drilled meters (mMD) in graph (b). The boreholes are classified by project type (white: heat project, black: power project) and drilling success (green: successful, red: unsuccessful due to low yields and yellow: unsolvable technical drilling problems). Also presented are the minimum, maximum and average values for thermal water temperature, borehole depth, borehole length, inclination and yield for heat and power projects.

2.2 Thermal Water Temperatures and Yields

The thermal water temperature and the amount of water that can be extracted from the aquifer sustainably are the limiting factors of a geothermal project. They determine the extractable energy and therefore control the design and type of the geothermal plant. An additional factor influencing the productivity of a borehole is the drawdown – how much the pressure/water level drops at a certain flow rate. Drawdown data was not available for this study and is therefore not presented.

As for the types of geothermal plants, there are several different set-ups tailored to exploit the given yields and temperatures. Heat projects typically transfer the heat of the thermal water via heat exchangers to the district heating fluid. Low temperature operations (<~60°C) use additional heat pumps to reach the necessary temperatures for a district heating system and/or use the thermal energy to heat thermal spas. For power projects the typical set-up is to transfer the thermal water temperature via heat exchangers to a working fluid (ammoniac-water mixture - Kalina or organic fluid - ORC) which itself vaporizes and drives a turbine to produce electricity via a generator.

Thermal water temperatures and yields of the 26 Bavarian projects are illustrated against the borehole depth in Figure 4 and against each other in Figure 5.

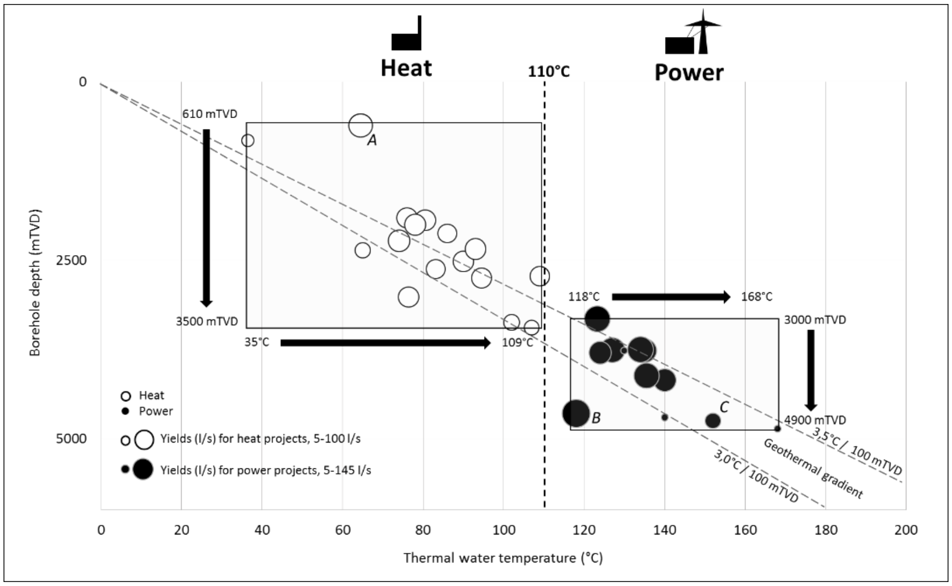


Figure 4: Yield of projects in the Bavarian Molasse Basin with respect to the total vertical borehole depth (mTVD) and thermal water temperature (°C). The black boxes represent the attribute ranges of the existing heat (white circles) and power (black circles) projects. Also shown is the 110 °C line, the thermal water temperature which was defined as the boundary between heat and power projects based on the currently operating geothermal plants.

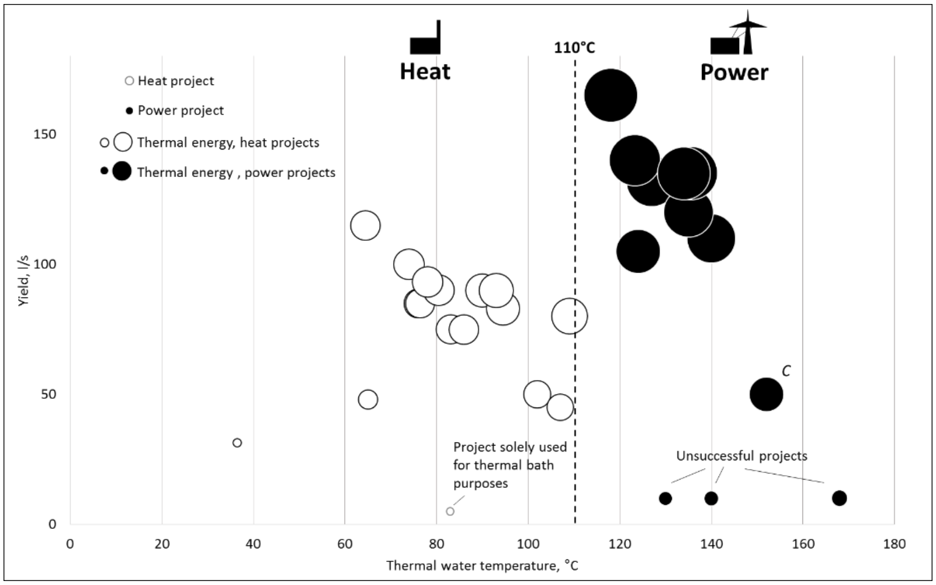


Figure 5: Yields and thermal water temperatures for the 26 production wells. The size of the circles represent the thermal energy as the product of the yield and the extractable temperature considering a minimum cooling temperature of 10°C. Also shown is the 110 °C line, the thermal water temperature that was defined as the boundary between heat and power projects based on operating geothermal plants.

The values of borehole depth versus thermal water temperature in Figure 4 plot fairly well along the average geothermal gradient in the Molasse Basin of 3.0 to 3.5°C per 100 mTVD (dashed grey lines in Figure 4). Two exceptions plot further away from the geothermal gradient, marked as A and B in Figure 4. Project A is located in the northern part of the Molasse Basin near the Landshut-Neuöttinger-Hoch and is thought to sit within a geothermal anomaly (Wrobel et al., 2002). Project B is situated in the south-eastern part of the Molasse Basin. Reasons for the lower than expected geothermal gradient for Project B are not known.

Figure 5 shows that the yields of power projects in the south German Molasse Basin generally reach more than 100 l/s and are in average higher than the yields of the heat projects. Exceptions on the power side are the three unsuccessful projects, with flow rates around or below 10 l/s and one power project with flow rates of about 50 l/s (C in Figure 4 and 5). This 50 l/s-project is nevertheless successful due to high thermal water temperatures, which compensate for the rather average flow rates. For heat projects there are various combinations of water temperatures and yields and as mentioned before, many different plant set-ups exist to efficiently use their specific temperature-yield ratio.

2.2 Drilling Costs and Drilling Progress

Drilling costs are a major investment position of the Bavarian deep geothermal projects. It can occupy from 40 to 70% of the total investment costs (Kölbel et al, 2012, Brasser et al, 2014). For the 26 projects and 75 boreholes in the south German Molasse Basin, a total of approximately 215 km were drilled (as of March 2018). Actual drilling costs for each borehole were not available for this study. However, based on averages (Lentsch et al. 2015, Schulz et al. 2017) an estimation of drilling costs was made, to compare the costs between heat and power projects as well as for first-try wells, sidetracks and deepenings. The results are summarized in Figure 6. The calculated costs include the actual drilling time, from rig arrival until rig removal, and other costs that are directly associated with the drilling operation such as bit changes, downhole measurements and others.

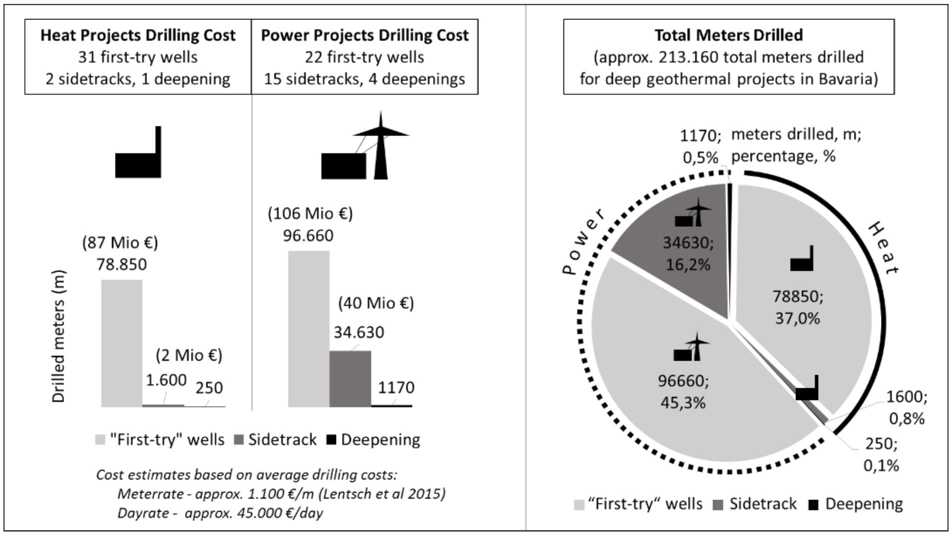


Figure 6: Estimated drilling costs and drilled meters for first-try wells, sidetracks and deepenings for heat and power projects (status March 2018).

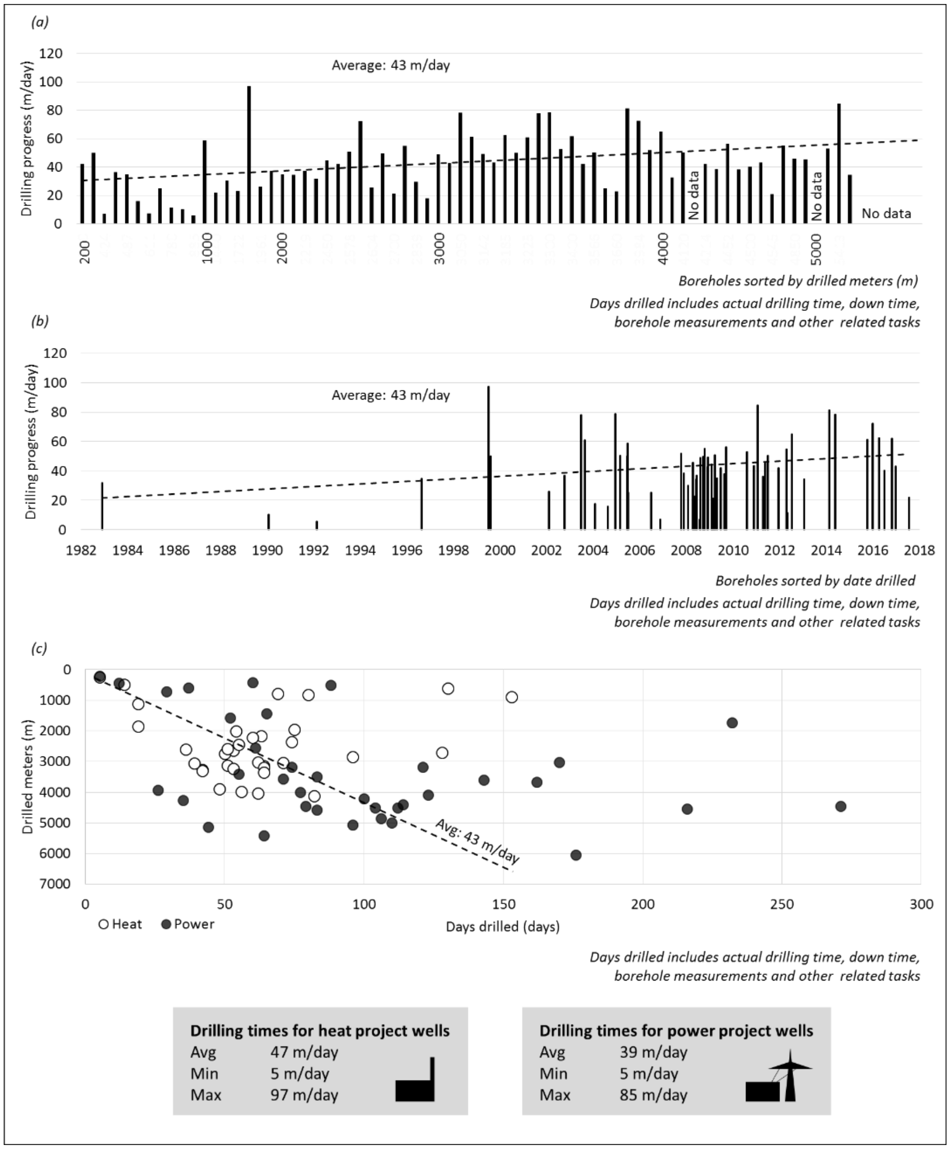
The drilling progress for each borehole is shown in graphs (a) and (b) in Figure 7 in meters per day. Graph (c) in Figure 7 shows the total amount of days needed to reach the target depth for each borehole. Some boreholes are not displayed due to missing data. It was assumed that the drilling time starts the day the rig begins to drill and ends once the target depth is reached. This includes downtimes, downhole tests, bit changes, running casing, cementing and other drilling related tasks. Excluded are the initial rig assembly times and the hydraulic tests, which are carried out after the borehole has reached its target depth.

Overall drilling progress ranges between 5 to 97 m/day, with an average of 43 m/day (Figure 7). Heat projects show a higher drilling rate with 47 m/d compared to 39 m/d for power projects. A slight increase in drilling progress towards longer boreholes can be observed in graph (a). The trend is however not clear, with many exceptions and outliers.

The same data set was sorted by the date the well was drilled and is illustrated in graph (b) in Figure 7. Assuming that drilling techniques advanced from 1982, when the first borehole was drilled, until now, drilling rates should have improved. A slight improvement over time can be observed. However, some projects still show below than average drilling progress.

Notably, the first borehole in 1982 was initially drilled as an oil and gas well, which was later converted and used as a geothermal well. The project itself started in 1998, 14 years later.

Drilling is a complex technical procedure carried out by different companies and drill rigs and it lies beyond the scope of this paper to define each aspect, which caused delays in the analyzed projects. Other publications have addressed this topic such as Brasser et al. (2014) or Lackner et al. (2018).



Drilling times for heat project wells	
Avg	47 m/day
Min	5 m/day
Max	97 m/day

Drilling times for power project wells	
Avg	39 m/day
Min	5 m/day
Max	85 m/day

Figure 7: Days drilled and drilling progress of deep geothermal wells (status March 2018).

2.2 Seismic Events

Until June 2018 eight microseismic events with magnitudes above $M_L = 2$ were recorded in the vicinity of three geothermal plants in Bavaria (Table 2). The commonly used limit above which a seismic event can be felt is magnitude $M_L = 2$ or higher (Erdbebendienst Bayern). In some cases, lower magnitudes can already be felt or heard, depending on the circumstances of the event, e.g. how densely populated the affected area is or the time and depth of the seismic event. Seven microseismic events occurred near the injection wells and one near a production well.

The triggers, leading to an induced seismic event, are not yet fully understood and are still being investigated. Some of the discussed factors are: regional and local stress field, orientation of fault systems in relation to the stress field, age of the fault and offset along the fault, continuation of fault systems into the underlying basement, chemical dissolution and re-precipitation effects caused by injected water, relationship between injection rate or total injected volume and triggered events, effect of pressure changes due to injection on the fault, thermo-mechanical effects caused by cooled off injected water and proximity of the injection well landing point to the underlying basement.

Table 1: Recorded seismic events of a magnitude above ML = 2. These seismic events could be felt or heard.

Location	Start of operation	Magnitude (M_L)	Date, Time	North	East	Depth (km)
Poing	2011	2,1	07.12.2016 05:28	48,191	11,794	~3,5
		1,8*	20.12.2016 03:30	48,189	11,789	3,4 +- 1
		2,1	09.09.2017 17:20	48,190	11,791	3,1 +- 1
Unterhaching	2007	2,3	10.02.2008 22:49	48,0459	11,6455	5,07
		2,5	03.07.2008 20:16	48,0470	11,6461	5,13
		2,1	21.07.2008 00:53	48,0466	11,6461	5,15
		2,0	02.20.2009 20:55	48,0462	11,6455	5,10
		2,1	27.05.2010 16:24	48,0479	11,6458	4,91
Aying/ Dürrnhaar	2013	2,0	29.04.2018 06:03	47,994	11,727	4

Source: Erdbebendienst Bayern (www.erdbeben-in-bayern.de); Megies, Wassermann (2014); *This below magnitude 2 event was also listed as it was felt by citizens.

3. RESULTS

In this study, we looked at available data for the 26 realized deep geothermal projects in Bavaria, concentrating on success rates and factors that can influence the outcome of a project. The analysis show differences between heat and power projects. The main analyzed factors are summarized in Table 2 below.

Table 2: Differences between heat and power projects regarding the reasons of unsuccessful boreholes.

	Heat projects	**Power projects**
Thermal Water Temperature	Thermal water temperatures: *35-109°C, Ø 83°C*	Thermal water temperatures: *113-168°C, Ø 137°C*
	Failure due to low temperatures has not occurred.	Failure due to low temperatures has not occurred. However, two projects encountered lower than expected temperatures. One project encountered 120°C instead of 140°C and the other 140°C instead of 160°C. One project was able to compensate the lower temperature by higher yields of around 140 l/s.
Yield	Yields: *30-100 l/s, Ø 74 l/s*	Yields: *50-145 l/s, Ø 112 l/s (<10 l/s for unsuccessful projects)*
	9% of the heat project wells did not encounter sufficient yields. Sidetracks eventually helped to encounter appropriate yields. The success rate of selecting productive target areas for heat projects can be considered as high. Exploration techniques are the same for heat and power projects, with 3D seismic campaigns becoming the standard (Lüschen & Thomas, 2012).	29% of the power project wells did not encounter sufficient yields. Sidetracks and deepenings helped to encounter appropriate yields for some of the boreholes. However, two boreholes remained unsuccessful. The success rate of selecting productive target areas for power projects can be considered as medium.
Technical Drilling Problems	Borehole depths (mTVD): *611-3500 mTVD, Ø 2280 mTVD* Borehole lengths (mMD): *611-4120 mMD, Ø 2663 mMD* Inclinations: *~10-90°, 9 straight, 25 angled* Inclined sections (m): *0-3950 m, Ø 1470 m*	Borehole depths (mTVD): *3000-4900 mTVD, Ø 4000 mTVD* Borehole lengths (mMD): *3025-6084 mMD, Ø 4650 mMD* Inclinations: *~15-60°, all 41 boreholes angled* Inclined sections (m): *945-4300 m, Ø 2660 m*
	None of the 34 heat project wells was unsuccessful due to drilling related issues. Heat project boreholes are on average shorter compared to power project wells. The inclined sections are often shorter as well.	24% of the power project boreholes were abandoned due to unsolvable drilling related problems. Power project wells are on average deeper than heat wells as they target deeper zones of the reservoir with temperatures above 110°C. All power project wells are angled and the angled sections are relatively long.
Gas	Natural gas has occurred at some of the heat projects but was manageable.	One power project encountered unsolvable gas related issues and was subsequently abandoned.
Seismic Events	Have occurred at heat projects.	Have occurred at power projects.

4. SUMMARY

The study summarizes the successes and issues of deep geothermal projects in the south German Molasse Basin. Analysis show that thus far there are two reasons that ultimately led to unsuccessful projects in Bavaria: insufficient yields and for one project natural gas. Overall three projects were unsuccessful, which were all power projects and situated in the deeper southern/south-western part of the south German Molasse Basin.

Regarding issues during the drilling stage, which led to the drilling of sidetracks or deepenings, analysis identified three major causes:

(1) Technical drilling problems, which have led to the drilling of nine sidetracks and delays in drilling operation. Thus far only power projects encountered technical drilling problems that ultimately led to sidetracks. This suggests that the deeper more inclined boreholes in the south have a higher risk of technical failure. A single reason for the increased drilling risk cannot be pinned down, as many factors play a role. These are among others: human error, material failure, pressure zones, time spent in the borehole, length of the inclined section or inclination of the borehole.

(2) Insufficient yields, which led to eight sidetracks, five deepenings and the abandonment of two projects. Deeper power projects, located in the southern and south-western part of the reservoir, show a higher risk of encountering insufficient yields. This suggests that there is still a lack of understanding of the deeper southern reservoir. The influence of parameters such as the depositional environment, diagenesis mechanisms, higher pressures and dolomitization, the connectivity of fault zones to permeable zones and others on the permeability seems to be not yet fully understood.

(3) Natural gas content, which led to delays during some drilling operations and to the failure of one project.

These three issues ultimately cause delays and increased investment costs and differ in their occurrence between heat and power projects.

5. CONCLUSION

The risk of not reaching the targeted temperatures and yields is still one of the most limiting factors for communities and investors to consider deep geothermal as an option for their energy supply. This however should be reconsidered and differentiated between heat and power projects. Based on the available data the success rate of heat projects is 100%, 14 out of 14. Furthermore, additional costs of heat projects associated with sidetracks or deepenings are very low as thus far only two sidetracks and one deepening had to be drilled. For power projects additional drilling costs are high, with 15 sidetracks and four deepenings and the success rate is 75%, 9 out of 12. The reason for the lower success rate of power projects seems to be the lack of understanding of the geological and hydrogeological setting of the deeper southern and south-western part of the reservoir in the south German Molasse Basin. This can and should however be improved by further research regarding the reservoir and investigating the unsuccessful projects. Apart from improving the understanding of the reservoir, it should be considered to utilize enhanced geothermal systems (EGS) techniques to improve the permeability and ultimately revive previously unsuccessful projects.

In order to enhance the economic benefit of deep geothermal projects and to ascertain the role of geothermal in the course of the energy and heat transition, the generation of geothermal heat or power shall not be more expensive than the average fossil fuel or renewable heat or power generation. This could be achieved by reducing drilling costs, which are often the main share of the investment costs and in addition avoiding sidetracks or deepenings, which further increase costs.

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