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Updated Stock Take of the Deep Geothermal Projects in Bavaria, Germany (2019)

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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. 29 deep geothermal projects have been realized in the Bavarian part of the South German Molasse Basin between 1998 and July 2019. In this paper, we provide an updated analysis of the current status of the southern Bavarian deep geothermal projects. The existing 29 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 or combined power/heat production, especially when it comes to success rates. Based on the available data the success rate of heat projects is 100 %, 15 out of 15 projects were successful. For power or combined power/heat projects the success rate is 71 %, 10 out of 14 projects. Power projects in the South German Molasse Basin target greater depths (>3000 m) to reach higher reservoir temperatures and require relatively high yields. This causes quite elaborate and rather long (sub-) horizontal drilling paths. Regarding the drilling success rate, our study shows that the success rate of first-try boreholes for heat projects is 91 %, three times higher than for power or combined power/heat projects with 32 %. Below a drilling depth of 3000 mTVD the probability of encountering low yields increases from 4 % to 25 % and of encountering technical drilling problems from 4 % to 20 %. Regarding additional drilling costs due to sidetracks or deepenings, analyses show that on average the additional costs for heat projects are about 40 € per drilled meter and for power projects about 265 € per drilled meter. On the subject of drilling rate, analysis show an overall average of 46 m/day, with heat projects showing a slightly higher drilling rate of 49 m/day compared to 41 m/day for power projects.

Thus far, four projects in Bavaria were unsuccessful. There are two reasons causing the failure of those projects: insufficient yields and for one project the natural gas content. All four unsuccessful projects are power projects and situated in the deeper southwestern part of the South German Molasse Basin.

Apart from exploration risks, higher thermal water temperatures that are naturally associated with power projects and higher yields are more likely to produce cost-intensive scalings than lower temperature thermal waters which are sufficient for direct heating use.

Observed induced microseismicity has occurred in both heat and power or combined power/heat operations, mainly at the reinjection well locations. Overall eight microseismic events with magnitudes between M_L = 2,0 and 2,5 and intensities between EMS II and EMS III have been observed at three locations thus far.

Power or combined power/heat projects are more ambitious than heat projects and awareness should be raised for the associated uncertainties and drilling risks. However, power production from geothermal resources especially in combination with heat production remains an important pillar for the energy transition in Germany. In order to increase the economic feasibility, drilling risks and the accompanying costs have to be reduced by a better understanding of the reservoir and the consideration of targeted small-scale stimulations.

1. INTRODUCTION

Between 1998 and July 2019, 29 deep geothermal projects have been realized in the South German Molasse Basin in Bavaria, Germany (Figure 1). 22 projects are operating, three projects have been or are being drilled and associated plants are currently in the planning or construction phase and four projects were unsuccessful (BVG 2019). All of these projects are hydrothermal projects, which tap into the deep carbonate aquifer of the South German Molasse Basin, with a thickness of about 400 to 600 m (Meyer & Schmidt-Kaler 1996). Out of the 29 projects, 15 are heat projects used for district heating and 14 are power or combined power/heat projects. Further projects are planned and are soon being drilled or finalizing their planning stage.

The total installed deep geothermal energy in Bavaria is 322 MW_{th} (Germany: 336 MW_{th}) and 35 MW_{el} (Germany: 37 MW_{el}) according to BVG (2019).

This study represents an update to Flechtner & Aubele (2019), in which the then 26 realized projects have been analyzed and evaluated.

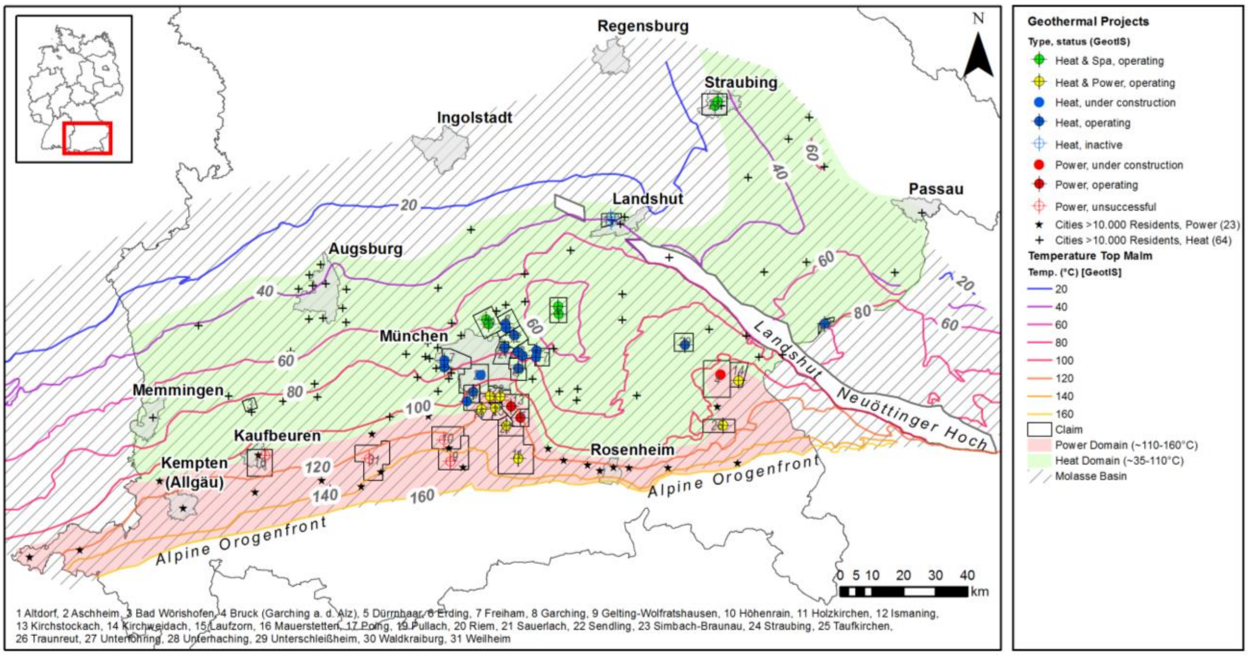

Figure 1: Locations of the deep geothermal boreholes and projects in the Bavarian part of the South German Molasse Basin (grey lines) along with heat (green) and power (red) favorability domains based on the Top Malm temperatures (GeotIS, 2019).

Our brief stock take gives indications of success rates and the settings of the 29 realized projects, in which several aspects of the project lifecycle were analyzed. The analyzed data was grouped into heat and power or combined power/heat projects, to be able to compare the two energy usages. Definitions of heat and power projects in the context of this study are as followed:

- Heat projects are defined as projects used for district heating or a combination of district heating and balneology. The thermal water temperatures in the Molasse Basin for direct heating use are up to 110 °C.
- Power projects are defined as projects used to generate electricity or projects that combine heat and electricity generation. Thermal water temperatures are above approximately 110 °C.

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

The 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 (Malm; Upper Jurassic) and thermal water temperatures of up to 160 °C. (2) Approval by authorities and acceptance in the local community. Communities can form initiatives to stop a project (before it has started) 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 and sufficient demand for the produced energy (e.g. direct heat demand). (6) Risk management of expected or unexpected events during the drilling stage or later plant operation, e.g. scalings, gas inlets, leakages in the plant or seismic events. Such issues can have an economic or social effect on the project and 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 (2019, Agemar 2014), the oil and gas database KW-FIS (2019) and the Energieatlas Bayern (2019).

2. RESULTS

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 be completed as 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 which can occur during drilling operations (e.g. broken casing or a stuck drill string) or by not reaching the required temperatures or yields, some wells are unsuccessful. Another reason for an unsuccessful borehole is the inflow of natural gas. One project in the south of the Molasse Basin first seemed to be unsuccessful due to insufficient yields. However, after additional hydraulic testing the yields seemed to be sufficient but 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 with technical problems or insufficient temperature and yields, 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. Other approaches to save a project include modifying or redesigning the plant to accommodate the encountered yields and temperatures or to change the economic concept and incorporate other end users (e.g. 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.

What is the success rate of drilling a deep geothermal well in Bavaria? In Bavaria, 84 boreholes were drilled for the 29 deep geothermal projects (status July 2019): 60 are first-try boreholes, 19 are sidetracks and five are deepenings. Figure 1 illustrates the 84 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).

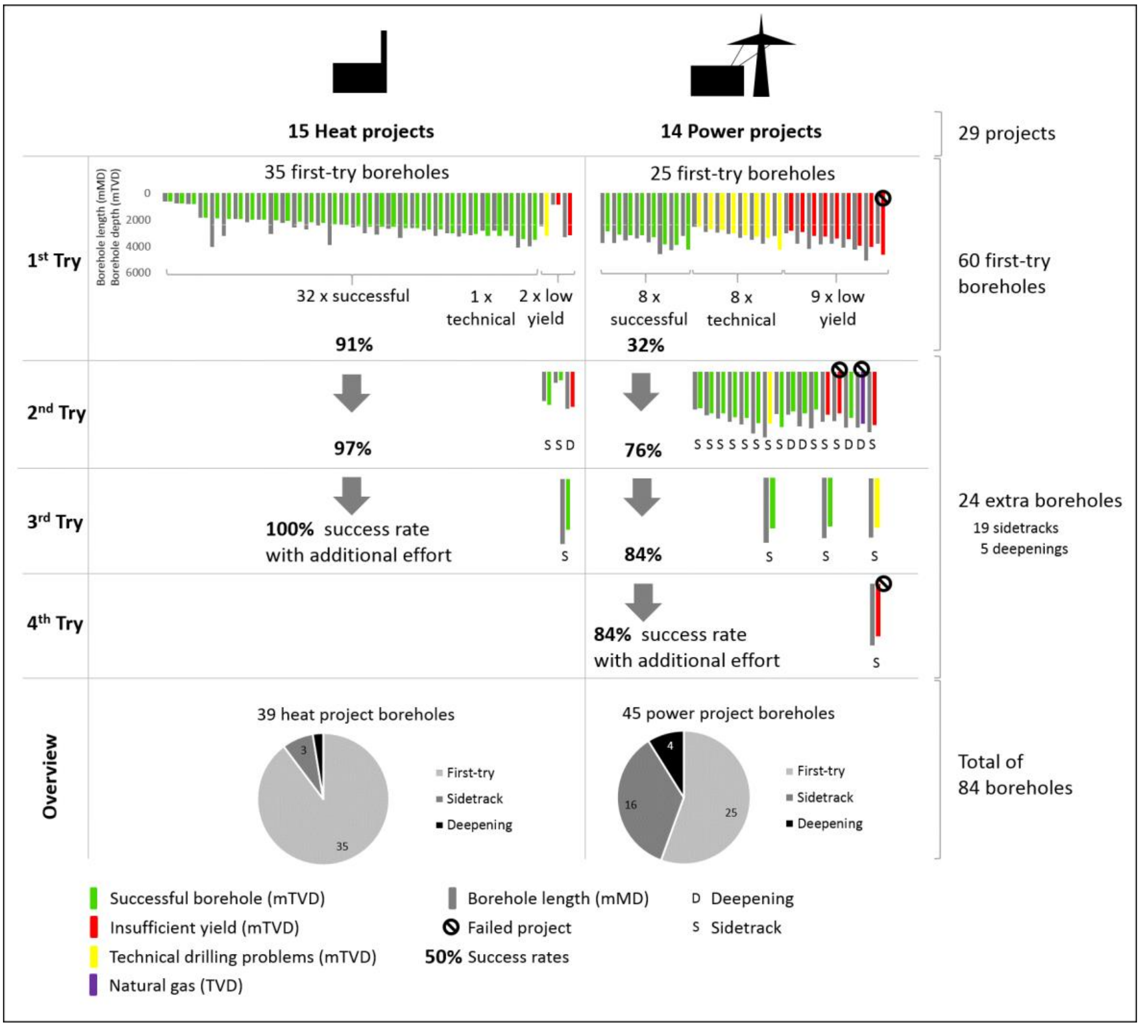

Figure 2: Drilling success sequence of the 84 deep geothermal boreholes in Bavaria, grouped into heat and power projects. It shows chronologically if holes were successful on the first try or needed additional tries. It also shows the depth of each borehole in mMD (grey) or mTVD (green, red, purple or yellow).

As shown in Figure 2, success rates and the number of additionally drilled sidetracks and deepenings differ between heat and power projects. The success rate of first-try boreholes for heat projects is 91 %, three times higher than for power or combined power/heat projects with 32 %. Wells that were unsuccessful due to technical drilling problems (yellow bars in Figure 2) occurred only one time for heat projects and 11 times for power projects. The total number of sidetracks and deepenings is 24, of which four were drilled for heat projects and 20 for power projects. With additional drilling effort (sidetracks or deepening), the success rate of heat projects increased to 100 % whereas for power projects the final success rate is only 84%. Thus four deep geothermal projects were unsuccessful (black crossed circles in Figure 2).

Figure 3 demonstrates the relationship between the drilled depth or length (meters total vertical depth: mTVD and meters measured depth: mMD respectively) and the success rate of a borehole. Unsuccessful wells with insufficient yields and technical drilling problems occur more often below 3000 mTVD and 3500 mMD. Above 3000 mTVD 4 % of the boreholes show low yields and 4 % technical drilling problems. In contrast, below 3000 mTVD 25 % of the boreholes show low yields and 20 % technical drilling problems. The borehole depth and the number of meters 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.

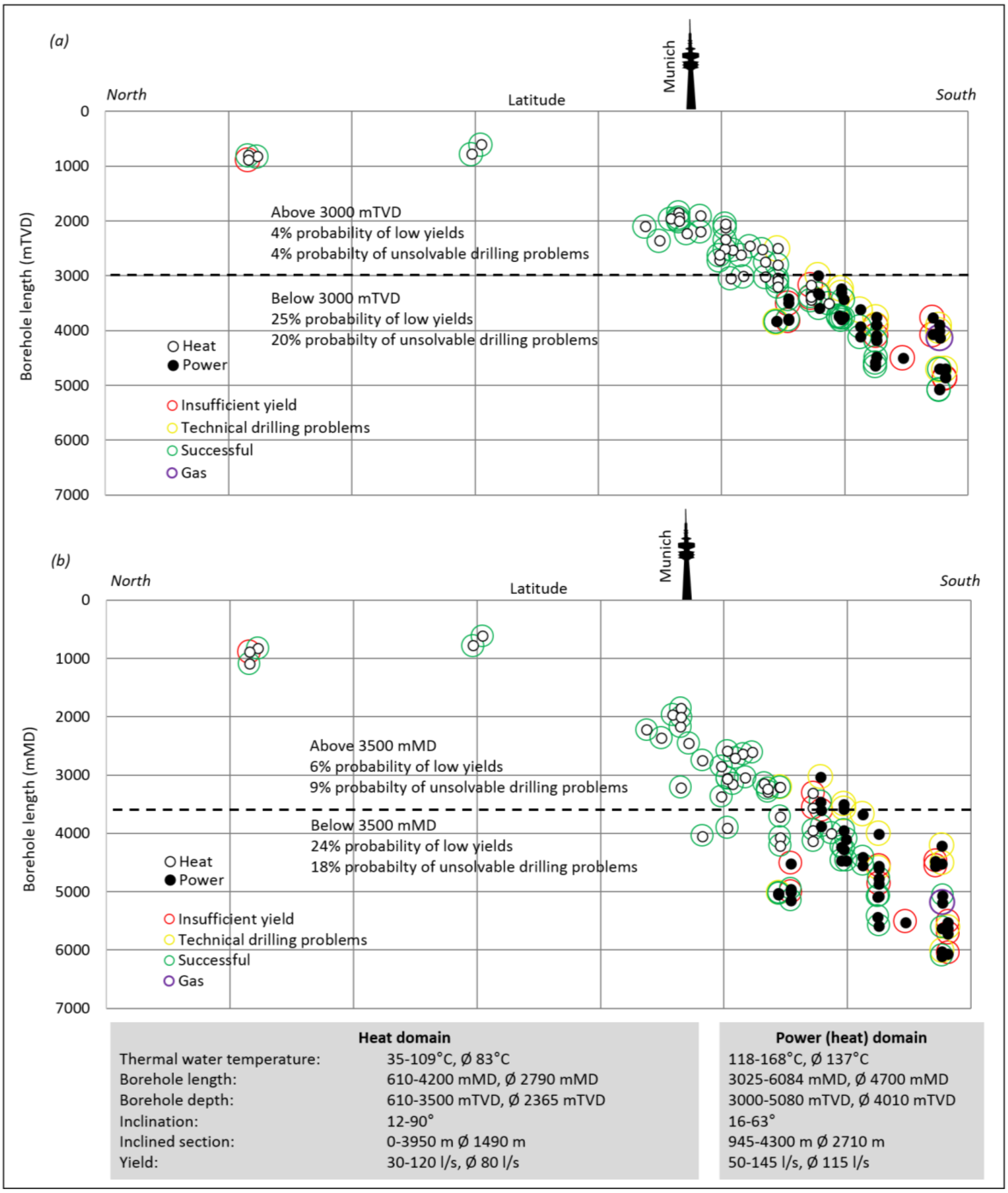

Figure 3: Drilling success of projects in the Bavarian part of the South German Molasse Basin with respect to mTVD in graph (a) and mMD in graph (b). The boreholes are classified by project type (white: heat project, black: power project) and drilling success (green: successful, red: unsuccessful due to low yields, purple: unsuccessful due to natural gas content 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 difference (ΔT) 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 output 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. However, 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. Power projects transfer the thermal water temperature via heat exchangers to a working fluid (ammoniac-water mixture - Kalina or organic fluids - ORC) which itself vaporizes and drives a turbine to produce electricity via a generator.

Thermal water temperatures and yields of the 29 Bavarian projects are plotted against the borehole depth in Figure 4 and against each other in Figure 5.

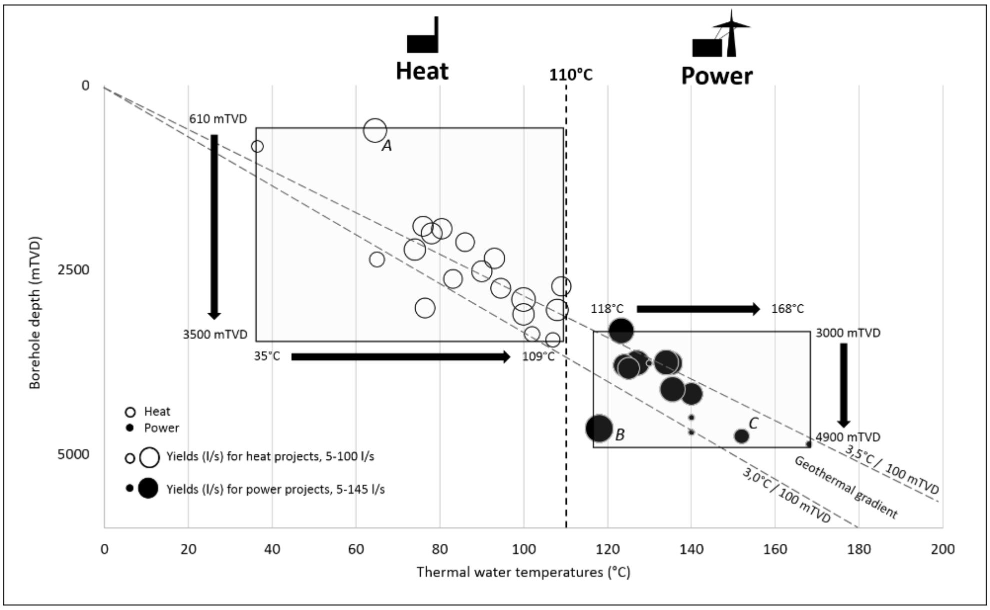

Figure 4: Yield of projects in the Bavarian part of the South German Molasse Basin with respect to the total vertical borehole depth (mTVD) and thermal water temperature (°C). The boxes represent the attribute ranges of the existing heat (white circles) and power (black circles) projects. Also shown is the geothermal gradient and the 110 °C -boundary which separates the feasibility for power generation from heating-only projects.

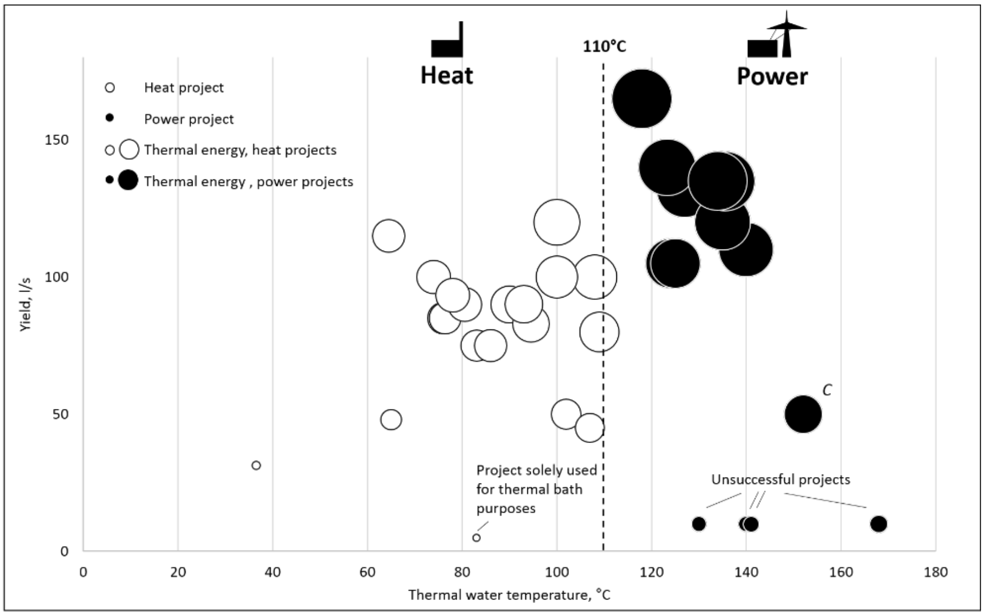

Figure 5: Yields and thermal water temperatures for the production wells. The size of the circles represent the thermal energy as the product of the yield and the extractable temperature considering a minimum cooling temperature of 10 °C. Also shown is the geothermal gradient and the 110 °C-boundary which separates the feasibility for power generation from heating-only projects.

The values of borehole depth versus thermal water temperature in Figure 4 match the average geothermal gradient in the Molasse Basin of 3.0 to 3.5°C per 100 mTVD (dashed grey lines in Figure 4) fairly well. 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 so called Landshut-Neuöttinger-Hoch and sits within a geothermal anomaly (Wrobel et al. 2002). Project B is situated in the south-eastern part of the Molasse Basin. Reason for the low geothermal gradient are currently unknown.

Figure 5 shows that the yields of power projects in the South German Molasse Basin generally reach more than 100 l/s and are on 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 project is nevertheless successful due to the high thermal water temperatures, which can compensate for the low yield using a different plant set-up.

2.2 Drilling Costs and Drilling Progress

Similar to most geothermal projects in the word, drilling costs are the major initial investment position of deep geothermal projects in Bavaria. It occupies between 40 to 70 % of the total investment costs (Kölbel et al. 2012, Brasser et al. 2014). For the 29 projects and 84 boreholes in the South German Molasse Basin, a total of approximately 239 km were drilled (as of July 2019). On average, 220 m of sidetracks and 20 m of deepenings are drilled per heat project and 1850 m and 90 m for power projects respectively. Actual drilling costs for each borehole were not available for this study. However, based on typical cost averages (Lentsch et al. 2015, Schulz et al. 2017) an estimation of drilling costs was made, to compare the costs of 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 or downhole measurements.

When breaking down the additional costs due to sidetracks and deepenings, the data shows that on average the additional costs for heat projects are about 40 € per drilled meter and for power projects about 265 € per drilled meter.

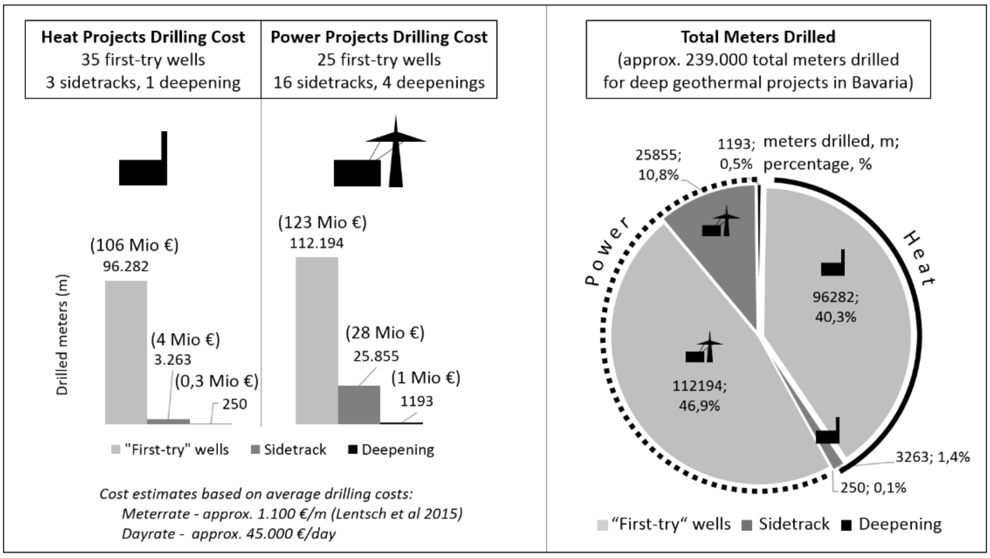

Figure 6: Estimated drilling costs and drilled meters for first-try wells, sidetracks and deepenings for heat and power projects (status July 2019).

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.

The drilling progress in the Molasse Basin ranges between 6 to 107 m/day, with an average of 46 m/day (Figure 7). Heat projects show a slightly higher drilling rate with 49 m/d compared to 41 m/d for power projects. A trend cannot be observed regarding depth and drilling progress.

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 have advanced from 1982, when the first borehole was drilled, until now, drilling rates should have improved. However, a slight improvement over time can be observed and some projects are still below the 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 address each aspect which caused delays in the analyzed projects. More information about technical issues can be found in Brasser et al. (2014) or Lackner et al. (2018).

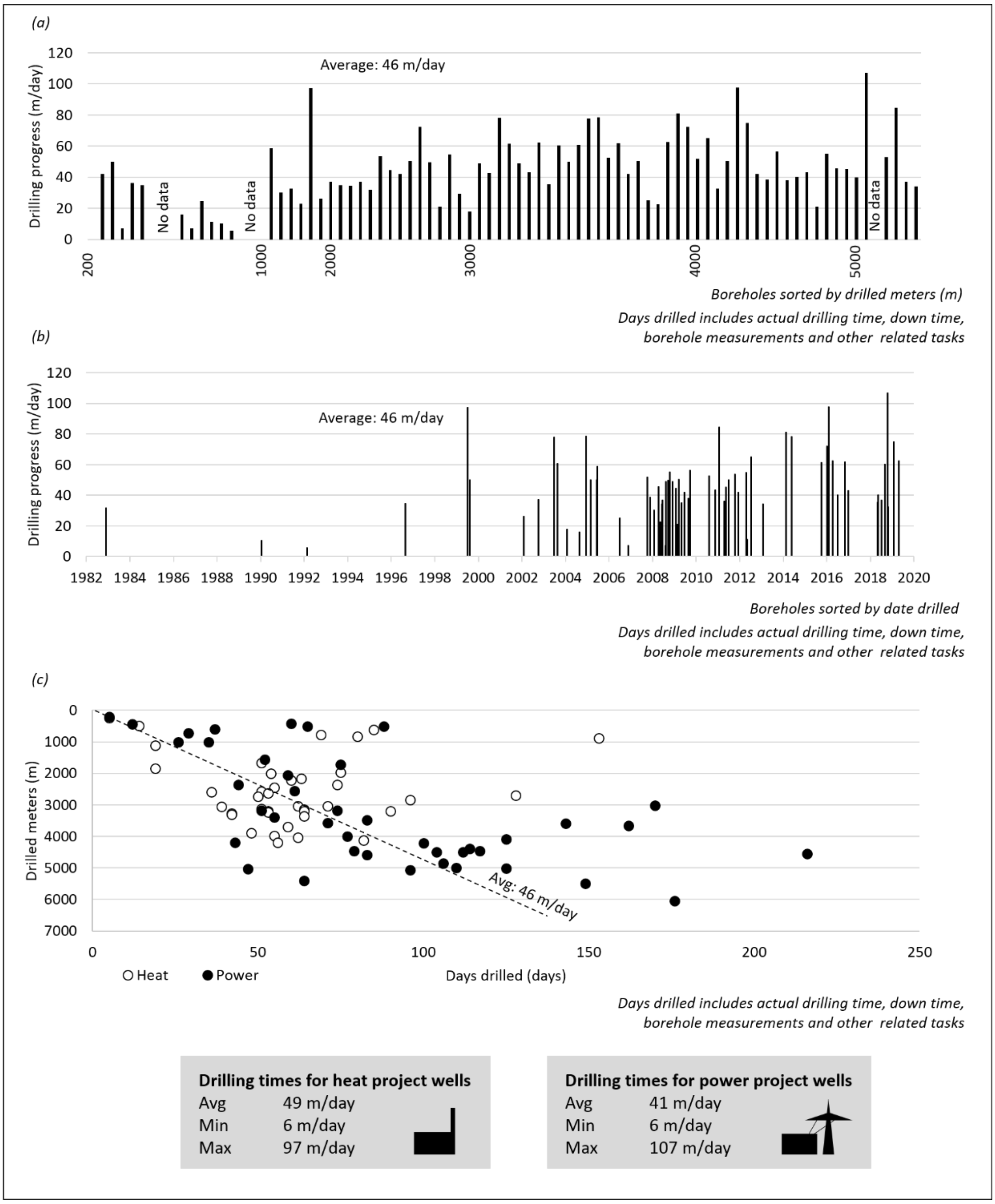

Figure 7: Days drilled and drilling progress of deep geothermal wells (status July 2019).

2.2 Seismic Events

Until July 2019 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 (EMS Intensity III; EMS-98) corresponds to magnitude $M_L = 2$ or higher, which however strongly depends on the source depth (Erdbebendienst Bayern). In some cases, lower magnitudes can already be felt or heard (EMS Intensity II), depending on the circumstances of the event, e.g. how densely populated the affected area is or the time of the seismic event. Seven microseismic events occurred near the injection wells and one near a production well.

The mechanisms leading to an induced seismic event are not yet fully understood and are being investigated (e.g. Drews et al. 2019 and Seithel et al. 2019). Some of the influencing factors which are being analyzed include: the orientation of regional and local stress fields, 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 (EMS Intensity II-III).

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	4,00

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

3. SUMMARY

In this study the available data of the 29 realized deep geothermal projects in Bavaria was analyzed, concentrating on success rates and factors that can influence the outcome of a project in the South German Molasse Basin. The results 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*	Thermal water temperatures: *113-168 °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: ~ *30-120 l/s*	Yields: ~ *50-150 l/s (<10 l/s for unsuccessful projects)*
	8 % of the heat project wells did not encounter sufficient yields. Sidetracks 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).	31 % of the power project wells did not encounter sufficient yields. Sidetracks and deepenings helped to encounter appropriate yields for some of the boreholes. However, three 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* Borehole lengths (mMD): *611-4200 mMD* Inclinations: *~10-90°, 9 straight, 30 angled* Inclined sections (m): *0-3950 m*	Borehole depths (mTVD): *3000-5080 mTVD,* Borehole lengths (mMD): *3025-6084 mMD* Inclinations: *~15-60°, all 45 boreholes angled* Inclined sections (m): *945-4300 m*
	Only one of the 39 heat project boreholes 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	Drilling and operation-influencing amounts of natural gas have occurred at some of the heat projects but were 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.

The analysis shows that thus far there are two reasons that ultimately led to unsuccessful projects in Bavaria: insufficient yields and for one project natural gas. Overall four projects were unsuccessful, which were all power projects and situated in the deeper southern/south-western part of the South German Molasse Basin. There are clear differences between heat and power projects. 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 11 sidetracks and delays in drilling operation. Thus far only one borehole for heat projects was unsuccessful due to technical drilling problems and ultimately led to the drilling of a sidetrack, whereas for power projects 10 boreholes were unsuccessful. 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 three projects. Two yield related sidetracks and one yield related deepening had to be drilled for heat projects, whereas for power projects six sidetracks and four deepenings had to be drilled. Deeper power projects, located in the southern and south-western part of the South Bavarian Molasse Basin, show a higher risk of encountering insufficient yields. This suggests that there is still a lack of understanding of the deeper reservoir in this area. The influence of parameters such as the depositional environment, diagenesis grade and 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 power project.

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

4. CONCLUSIONS

The risk of not reaching the targeted temperatures and yields is still one of the most limiting factor for communities and investors to consider deep geothermal as an option for their energy supply. This, however, should be reconsidered and a clear differentiation has to be made between heat and power projects. Based on the available data, the success rate of heat projects is 100 %, 15 out of 15 projects were successful. Furthermore, given the low number of sidetracks (three) and deepenings (one) that were required to complete the heat projects, additional costs and therefore the economic risk is very low. The success rate of power projects is 71 %, 10 out of 14 projects were successful. The average additional drilling costs for power projects are higher, as overall 16 sidetracks and four deepenings had to be drilled so far. The lower success rate of power projects shows that there are still knowledge gaps, especially in the deeper southern area of the South German Molasse Basin. To better understand the deeper reservoir, further research is necessary regarding reservoir exploration and the investigation of the unsuccessful projects. Apart from improving the understanding of the reservoir, advanced stimulation techniques should be considered in the future, 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 must not be more expensive than the average fossil fuel or renewable heat or power generation. A greater competitiveness could be achieved by reducing drilling costs, which are often the main position of the initial investment costs as well as avoiding sidetracks or deepenings, which further increase costs.

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