

Five Years of Permanent Fiber Optic Monitoring in Deep Geothermal Wells in Munich: Lessons, Insights, and Evaluation

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ABSTRACT

Over the past five years, a permanent fiber optic monitoring (FOM) system has been implemented at Germany's largest geothermal site in Munich to enhance the understanding of the reservoir and processes in the wellbore. Three deep geothermal wells were equipped with fiber optic cables using cemented and suspended installation methods, enabling continuous Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS), and point pressure monitoring. This setup has provided valuable insights into reservoir dynamics, such as flow zone characterization, well interactions, and seismic monitoring, as well as borehole-specific assessments, including cementation quality and ESP performance. The long-term performance of the FOM system under harsh geothermal conditions confirms its robustness and utility. This paper reviews key use cases, installation methods, and the comparative benefits of fiber optic sensing over conventional approaches in deep geothermal applications.

1. INTRODUCTION

The Upper Jurassic carbonate rocks in the South German Molasse Basin hold a large reservoir of thermal water for deep geothermal direct use and power generation. The formation is already exploited by 25 plants in Bavaria, and there are plans to extensively develop the field (Fink and Klitzsch 2022). To understand the complex geologic heterogeneity of the subsurface for future development and ensure the production and operational reliability of geothermal plants and their efficiency, the reservoir and specific sites are the subject of various scientific studies (e.g. Zosseder et al 2022).

Recording downhole data in wells can often be both time-consuming and costly, and in some cases, it may even be impossible during certain operational phases. For instance, data from below the electronic submersible pump (ESP) is unavailable during production or injection stages. This limitation complicates observing processes occurring in deeper sections and within the reservoir. To improve our understanding of various facets of geothermal operations, including the long-term hydraulic, thermal, and mechanical behaviors in geothermal boreholes and reservoirs, we have opted to install a permanent fiber optic monitoring (FOM) system at a geothermal site.

The 'Schäftlarnstrasse' (SLS) plant is Germany's largest and most extensively studied deep geothermal site, making it the ideal location for an innovative monitoring system. The reservoir is targeted by six deviated wells, with depths ranging from 2,250 to 3,100 meters true vertical depth (TVD) (Fig. 1). Collectively, these wells produce up to 280 L/s of thermal water at temperatures between 95 and 108 °C, equating to a thermal output of 60 MW. We have permanently equipped three of these wells with fiber optic cables (FOC), enabling high-resolution Distributed Temperature Sensing (DTS) for precise temperature monitoring, as well as Distributed Acoustic Sensing (DAS/DDSS) for acoustic/dynamic strain measurements. Additionally, continuous pressure monitoring is facilitated by fiber optic gauges positioned at both the top and bottom of the reservoir.

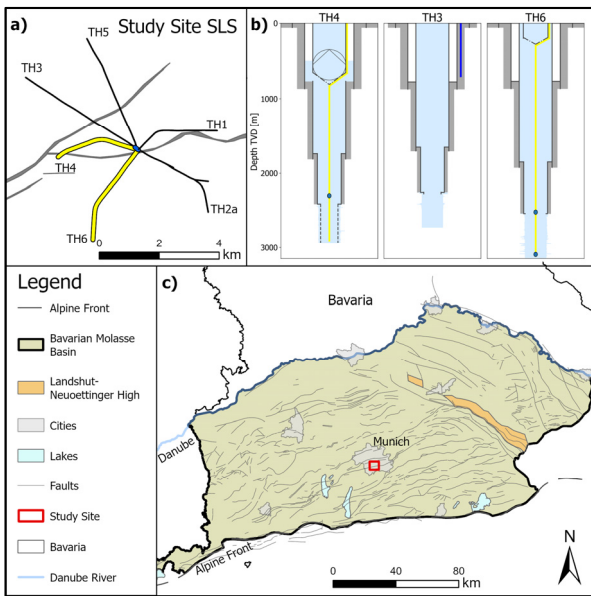


Figure 1: Overview of study area and site. a) Well paths. b) Well sketches with FOCs. c) Map of South German Molasse Basin and location of study site in Munich.

The FOCs were installed using two distinct methods. One injection well (TH3) features a cable that is cemented behind the casing in the first section of the well, reaching approximately 650 m MD. In contrast, one producer (TH4) and one injector (TH6) have cables suspended inside the wellbore, attached to sucker rods, reaching total depths of 3650 m and 4100 m MD, respectively. The innovative installation of cables on sucker rods has demonstrated that it is feasible to permanently install FOCs in wellbores, even under challenging conditions such as high well inclination and open-hole reservoir sections. Due to the differing construction designs, the coupling to the formation and the maximum depth of the two FOC types vary, leading to distinct use cases and methods applicable to the DTS, DAS, and pressure data.

Since 2019, we have continuously recorded DTS data with high temporal (10 min) and spatial resolution (1 m) in wells TH3 and TH4 during shut-in and operational phases. Starting in 2024, DTS data has also been permanently collected in well TH6. Over the years, we have conducted several month-long DAS campaigns across all three wells, encompassing various operational stages and experimental setups. In addition, we continuously monitor pressure and temperature using fiber optic point sensors in the reservoir located in TH4 and TH6.

The acquired DTS, DAS, and pressure data have provided valuable insights into the target carbonate aquifer's thermal, hydraulic, and mechanical characteristics and dynamics, enhancing our understanding of its behavior during geothermal operations. DTS analysis has proven particularly effective in identifying flow zones, tracking thermal and hydraulic changes over time, and monitoring well interactions. Meanwhile, DAS data has been instrumental for microseismic monitoring, assessing the cementation process, conducting vertical seismic profiling (VSP), and pump monitoring, providing a comprehensive well-functioning perspective.

2. OVERVIEW OF FOM USE CASES

In this paper, we categorize the use cases and methods of fiber optic monitoring into two distinct groups: one focusing on subsurface characterization and monitoring, and the other on borehole systems and their technical components. We primarily highlight the key methods that have been applied and assessed at our study site. Additionally, we performed a literature review on fiber optic applications in boreholes, evaluating their relevance to geothermal energy applications. Table 1 provides an overview of all the use cases discussed in this paper, which we will elaborate on in the following sections. Figure 1 displays the installed FOM system, the key use cases, and conventional options for addressing these.

Table 1: Overview and evaluation of fiber optic monitoring topics.

Topic	Implementation at study site	Implementation in literature	Quality compared to conventional
Subsurface characterization/-monitoring			
PT Reservoir monitoring	★★★	★★★	★★★
Flow zones localization/monitoring	★★★	★★★	★★★
Interaction between wells	★☆☆	★☆☆	★★☆
Fluid level -> injectivity/productivity index	★★☆	★★☆	★★☆
P/S wave velocity model (VSP)	★★★	★★★	★★☆
Structural imaging (VSP)	★★☆	★★★	★★☆
Seismic monitoring	★★☆	★★☆	★★☆
Borehole (technical components) monitoring			
Cementation 1. section	★★★	★★☆	★★☆
ESP monitoring	★★☆	★★☆	-
Leakage	☆☆☆	★★★	-
Corrosion/Scaling of casing/tubing	☆☆☆	★★☆	-

2.1 Subsurface characterization and monitoring

Monitoring of the subsurface during various stages of geothermal projects is essential. Some efforts at our study site focus on general reservoir characterization to support the geothermal field development. In contrast, others concentrate on operational monitoring and optimizing specific processes at the wells/site. DTS and FO-P/T data have been analyzed to thoroughly assess the initial thermal and hydraulic conditions of the reservoir (Schölderle et al 2021). Over time, during operation, this data has been instrumental in monitoring the productivity and injectivity of the wells.

At the site, flow zone detection and monitoring utilizing DTS and DAS were conducted using various methods (Schölderle et al 2023). These included warmback analysis during shut-in following water injection, thermal slug tracing during water injection, production profiling with analytical models, and low-frequency DAS to detect flow velocities in the reservoir. As a result, the permeability distribution within the reservoir and geophysical correlations of the formation and flow zones were effectively established. The level of detail captured in both space and time surpasses that of conventional logging.

While some assessments can be accomplished using conventional logging or sensors, many insights are only attainable with FOCs in the wells. For instance, the injection wells at the site do not have downhole P/T sensors, therefore injectivity cannot be monitored. Although production logging is conventionally utilized to detect flow zones in the reservoir, it is limited to periods when the system is shut in and therefore not suitable for permanent monitoring as with FOM.

The additional pressure data and DTS information provide valuable insights into the interactions between the wells at the site. This data also serves as a solid foundation for developing numerical models of the reservoir to investigate flow pathways.

In literature, DAS is frequently utilized for seismic monitoring (e.g. Lellouch and Biondi 2021). At our site, we have tested the two setups of FOC in boreholes for microseismic monitoring. A six-month campaign was conducted at the site using a cemented cable in well TH3 (Azzola and Gaucher 2024). The results demonstrated that DAS effectively detects seismic events, and integrating FOC into the existing conventional seismic monitoring system represents a significant enhancement. The suspended cable FOC in wells TH4 and TH6 can also be utilized, albeit with certain limitations. It was observed that during production and injection, the noise levels in the cased sections due to water movement are excessively high;

however, seismic events are visible in the deep reservoir where less fluid movement noise is present.

The suspended cable in well TH4 allowed recording an active Vertical Seismic Profiling (VSP) during shut-in periods, presenting a viable alternative to temporarily placing geophones in the well. However, it remains uncertain whether VSP would be feasible during production/injection due to the noise generated by flowing water. While coupling—and thus signal strength—declined with increasing depth, signals were still detectable down to bottom reservoir. Additionally, the energy source at the surface was primarily aimed at well TH1, which has an opposing well path, leading to some limitations in signal quality/strength.

Applying VSP could serve for structural mapping and aligning with surface active seismic models. It may also contribute to developing a P/S wave velocity model for the site. Furthermore, monitoring changes over time in the P/S wave velocity field could theoretically provide insights into the propagation of the cold front between the injection and production wells.

2.2 Borehole (technical components) integrity and monitoring

In a study conducted on well TH3, we thoroughly analyzed and monitored the entire cementing process for the first section (Hart et al 2025). We used DAS and DTS to track rising fluid interfaces, oversee the cement's setting time, and evaluate the cement quality at various depths. This allowed us to effectively monitor and assess cement displacement, spacer/wash efficiency, potential zonal isolation, and gas flow in the annulus.

In geothermal settings like at our study site, electronic submersible pumps (ESP) are prone to failure, which poses a high financial risk for operators. Efforts in a recent research project at the site focus on including DAS and DTS to detect early warning signals for ESP anomalies. For that, the frequency patterns at the pump are studied with the goal of implementing machine learning algorithms for automated detection of features and deviation from the standard patterns.

The overall integrity of the casings and tubings is essential and FOM can help to monitor it. For example, thermal and mechanical stress on these components can be analyzed using DAS and DTS data to estimate their theoretical wear. Numerous studies in the literature have utilized FOM for detecting potential leakage, corrosion, or scaling of casings (e.g. Cherubini et al 2023). However, in our case, no such issues have been observed, which is why the detection methods have not yet been tested or verified at the site.

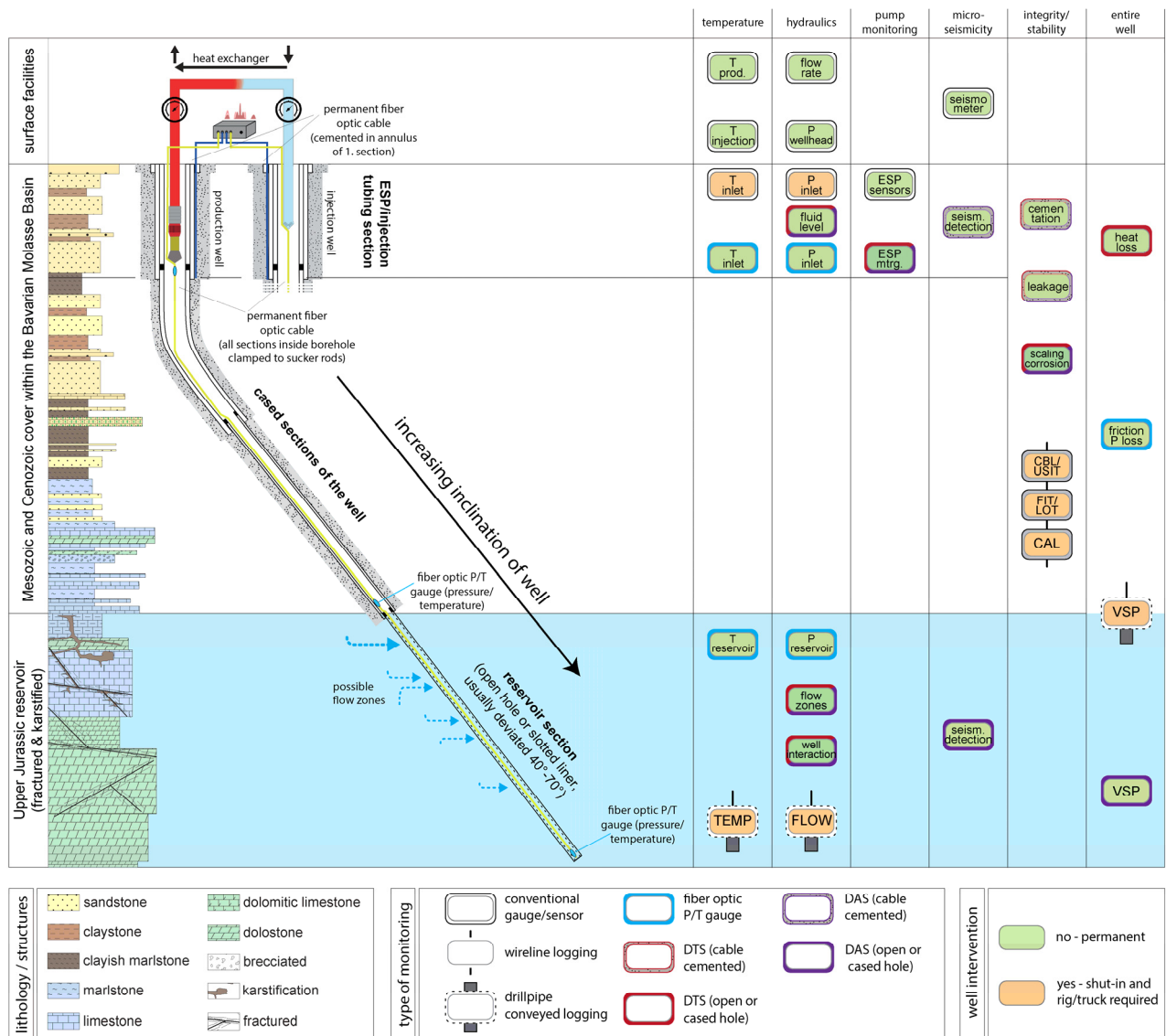


Figure 2: Overview of uses cases for fiber optic monitoring systems in deep geothermal wells as implemented at study site SLS in Munich.

2.3 FOC installation details

The study involves the installation of fiber optic cables using two different designs. Cementing cables behind the casing is a common practice in both the oil and gas industry as well as in geothermal wells. In this design, the FOC is clamped to the outside of the casing in the first section before the cementing process. While this method provides excellent coupling to the formation, it poses significant technical challenges for deeper installations, which limits data accessibility and prevents measurements within the reservoir. Additionally, the installation of supplementary FO-P/T gauges is not feasible with this approach.

Clamping the FOCs to sucker rods and suspending this assembly within the borehole allows for a permanent installation of the FOC that offers several advantages, albeit with some challenges/risks. This configuration enables the cable to remain in the wellbore during production and injection phases. Its stiff design facilitates deployment in highly inclined and even open-hole reservoir wells down to TD. However, not

damaging the cable mechanically during installation or workover can be challenging. Despite this, successful repairs have been achieved by splicing the fibers together on-site. This installation option provides direct DTS/DAS signals of the thermal water. However, depending on the well's inclination and position within the wellbore, it has a variable and often less effective coupling to the formation. A customized cross-over from the ESP or injection tubing to sucker rods had to be specifically designed and manufactured. Furthermore, integrating multiple FO-P/T gauges into this design is also feasible.

3. CONCLUSIONS

At our study site, we have demonstrated the feasibility of permanently installing fiber optic cables in deep geothermal wells utilizing various installation designs. These cables have withstood harsh conditions—including high pressure, temperature, and the presence of hydrocarbons—for over five years without showing any signs of degradation. Throughout this period, we

have applied several methods to analyze the DTS and DAS data.

The possibilities and methods for FOM in deep geothermal boreholes are quite varied. While conventional techniques utilizing logging or permanent downhole sensors remain viable for certain applications, our findings indicate that DTS and DAS methods sometimes provide superior solutions for many use cases. Several key applications hold significant relevance for the geothermal operator at our study site, particularly since conventional monitoring options are unavailable for these scenarios.

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