Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Potential of Multilateral Wells for Geothermal Projects in the South German Molasse Basin

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Keywords: multilateral wells, multilateral completions, multilateral technologies, geothermal well design, South German Molasse Basin, hydrothermal resources

ABSTRACT

Over the last two decades, the development of geothermal energy has increased rapidly in the South German Molasse Basin (SGMB). By making use of one of the most promising geothermal reservoirs in Central Europe, more than 20 geothermal plants, providing both electrical power and heat to thousands of households, have been put on stream successfully, with many more to come. Along with the increasing interest in the geothermal potential, well design has evolved over the years. At present, wells can be drilled reliably and cost-effective to depths of about 5,000 m depth, delivering production rates of 50 - 160 l/s. However, suitable drilling locations in the South of Germany are scarce and very expensive, especially in Munich and the vicinity. Therefore, the geothermal energy output of each drilling location must be maximized. The well design and the exploration strategy must be adjusted to reach this goal. So far, the well design focused on minimizing cost and risk while providing a defined yield. "Keep it simple" was the guiding principle of many well designs. For future wells, maximizing the production per well site and minimizing the surface footprint will be the most important goal. To reach this, a range of measures is available, one of them being multilateral technology. Multilateral wells allow the exploitation of a reservoir through several wellbores (branches) originating from one motherbore. In utilizing this approach, the drainage area can be increased while reducing the inflow pressure losses for each well. In this paper, analytical methods and results from a numerical reservoir simulation are used to discuss the concept and its theoretical potential. In addition, the technical aspects of different multilateral technologies are assessed regarding the applicability for geothermal projects in terms of technical suitability, costs, risks, and regulatory requirements. The outcome of this study is the basis for the first multilateral geothermal test well in the South German Molasse Basin, which is drilled and tested during 2020 in Munich.

1. INTRODUCTION

1.1 The Role of Geothermal Energy in Germany and Munich

The awareness for climate change is growing in our society, and the need for more sustainable energy sources is rising. Most national programs, however, focus on the question of how to meet the electrical energy demand, neglecting the fact that almost 50% of the energy consumed in Germany is used to provide heating. In 2018, 37% of electrical energy but only 14% of heating demand was generated by renewable energy. Only 0.7% (1133 GWh) of the heat supply is generated from deep geothermal sources so far. (AGEE-Stat and Umweltbundesamt, 2019)

In the past, most of the drilling activity in Germany for deep hydrothermal wells was focused on the Upper Rhine Graben, the North German Basin, and the South German Molasse Basin. With 26 deep geothermal projects realized between 1998 and March 2018, the South German Molasse Basin is the most developed of those regions. (Flechtner and Aubele, 2019)

Within the basin, Munich is situated in the center. Therefore, the utilization of geothermal energy for heating will play a major role in meeting the city's energy targets, counting 1.5 million citizens. The municipal utility company of Munich, the "Stadtwerke München" (SWM), has set the goal of supplying their district-heating network with 80% of geothermal energy by 2040. (SWM, 2018)

1.2 Geological Setting and Reservoir Characteristics

The Malm aquifer, Germany's best-explored geothermal reservoir, is situated within the region of the South German Molasse Basin, a typical sedimentary peripheral alpine foreland basin of late Eocene to Miocene age. The aquifer itself is a highly permeable carbonate reservoir of Upper Jurassic age at the base of the asymmetric basin (Lemcke, 1988). It reaches a thickness of up to 600 m (Meyer and Schmidt-Kaler, 1996). However, the pay zone of the reservoir depends on the facies distribution and depth of diagenetic processes, and its thickness is often lower than the Malm thickness (StMWIVT, 2004).

Towards the south, the depth of the reservoir increases up to > 5000 m true vertical depth (TVD). Along with this increase, the thermal water temperature rises to maximum values of 150-160°C. The average geothermal gradient in the Molasse Basin is approximately 30°C/km. On a local scale, however, positive and negative thermal anomalies appear (StMWIVT, 2004).

Within this limestone, the porosity and permeability are strongly governed by the facies of the rocks. Reef limestone (mass facies) is favorable in terms of hydraulic conductivity. Bedded or layered marly limestone, on the other hand, shows lower or no hydraulic conductivity. Moreover, diagenetic processes (primarily dolomitization and karstification) affect hydraulic conductivity. Additionally, faults with a displacement of 150 m to 200 m are present. (Stier and Prestel, 1991; Andres, 1985; Frisch and Huber, 2000; Boehm et al., 2013; Bachmann et al. 1982; and Bachmann et al. 1987)

The pore pressure of the Malm aquifer is below hydrostatic. In and around Munich, the static water level in the well is typically between 100-200 m below surface, strongly depending on local altitudes (StMWIVT, 2004).

Figure 1 shows a sketch of the geological cross-section of the basin, indicating the reservoir temperature in different regions.

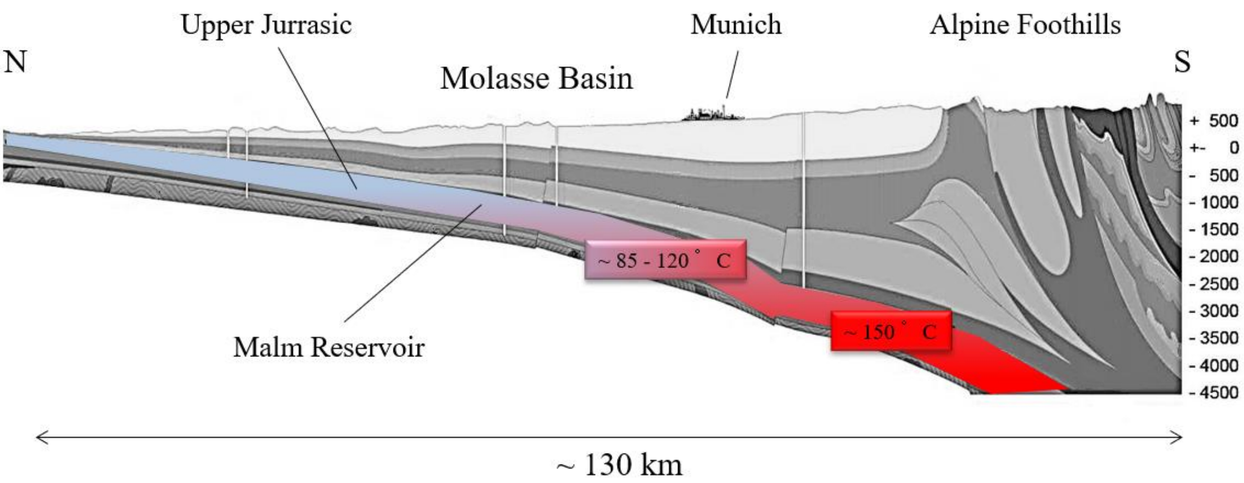


Figure 1: Sketch of the geological cross-section of the Molasse Basin (Adapted from Bayerisches Geologisches Landesamt, 1996)

1.3 Hydrochemistry

The aquifer water is generally classified as low mineralized (TDS mainly around or less than 1g/l). At the northern border of the basin, calcium, magnesium, and bicarbonates are the dominant aqueous species. Typically, higher dolomitization results in higher magnesium content. Typical for the Malm groundwater is a surplus of sodium over chloride, which can be explained by admixture from external sources, as the Malm carbonates themselves contain only little sodium. The sulfate concentrations decrease from the northern edge of the basin to the center of the basin, as sulfate is reduced to sulfide at higher temperatures. The resulting H_2S is detectable in all Malm water samples. The occurrence of hydrocarbons is known as well. (StMWIVT, 2004)

1.4 History of the Geothermal Development in the South German Molasse Basin

The initial use of the reservoir started decades ago when the thermal water of unsuccessful (dry) oil wells was used for thermal spas (Nathan, 1949; and Gabauer, 2000).

In 1990, the first geothermal well for heating was drilled (Figure 2). For the first seven years of the millennium, only a few geothermal projects were realized. However, in 2008 the drilling activities increased rapidly. The factors for this period of rapid growth were: Firstly, the publication of the "Bavarian Geothermal Atlas" (cf. StMWIVT, 2004), which provided a comprehensible overview of the geothermal potential of the Malm aquifer, secondly the introduction of increased remuneration for geothermal energy generation projects through the Renewable Energies Act (Erneuerbare-Energien-Gesetz, EEG), and thirdly the introduction of market incentive programs providing subsidies and low-interest loans for geothermal heating projects. (Dorsch and Pletl, 2012)

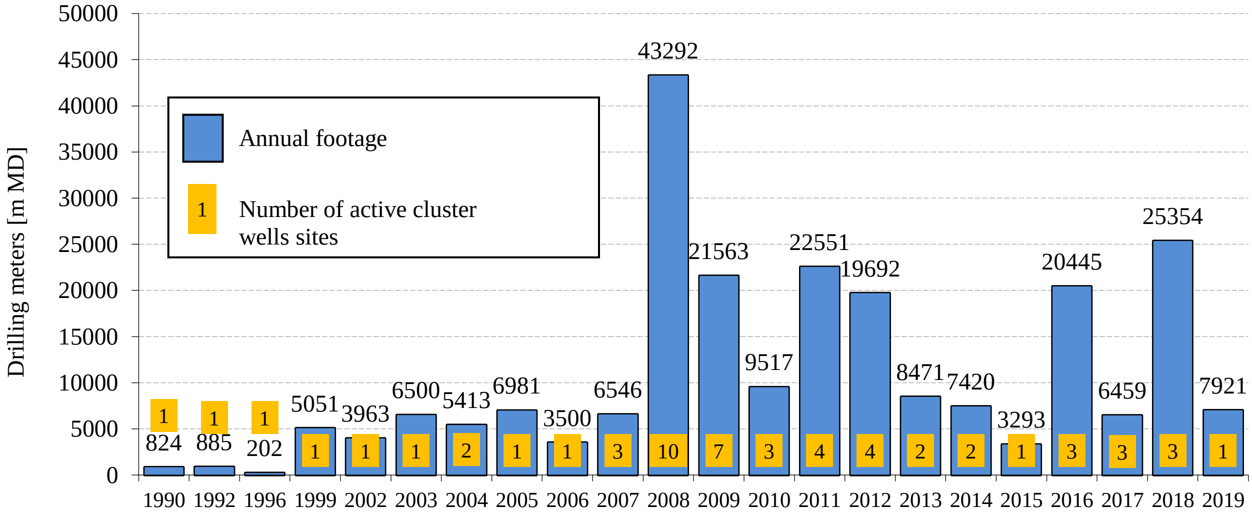


Figure 2: Annual geothermal drilling footage (measured depth, MD) of deep geothermal projects in Bavaria, Status: June 2019 (Adopted from Bendias et al., 2019)

So far, 26 projects have been realized in total (status March 2018), with 14 district heating projects and 12 power or combined power/heat projects. Three out of the 26 projects were unsuccessful due to insufficient yield or technical problems. (Flechtner and Aubele, 2019)

The exploration started in the northern and central parts of the Molasse Basin with drilling depths of a max. 3,000 m measured depth (MD). In more recent years, the exploration has moved southwards, and along with this, the drilling depths of the deviated wells have exceeded 6,000 m MD. (cf. Lentsch et al., 2015; cf. Lackner et al., 2017)

1.5 Well Design - State of the Art

For the well design in the Molasse Basin, several distinctive attributes are to be considered. The most essential are:

1) Thermal water is produced with high flow rates above 50 l/s up to 160 l/s directly through the casing string up to the electrical submersible pump (ESP) intake. This requires large-diameter boreholes to reduce friction pressure losses and protection of the casing during drilling to avoid erosion (e.g., due to drill string rotation) to ensure long-lasting well integrities. Installations with small inner diameters (IDs) must be avoided to reduce friction pressure losses.
2) The risk of borehole instability and fines production in the reservoir section is minor. Therefore, the completion is barefoot, or a perforated liner is installed.
3) Large outer diameter ESP pumps are installed to a depth of typically up to 900 - 1000 m. The casing diameter must be large enough to run the ESP in this upper section. The well path must be straight in this section to avoid bending of the ESP.
4) The decision about which of the well(s) of a project is a producer or injector is made after the final well tests. Therefore, each well must be designed for the production and the injection scenario. High compression loads in the upper part of the well are typical due to high production temperatures. Collapse loads are critical due to the pressure drawdown during production, especially along with formations with increased pore pressures. Additionally, high tensile loads appear typically in the lower part of the casing due to a temperature decrease during reinjection.
5) Lost circulation in the reservoir section requires special consideration in drilling and casing design.
6) The wells drilled in the southern and deeper part of the basin require additional demands on the drilling technology due to over-pressurized zones caused by disequilibrium compaction overpressure (Drews, 2018). The wells in the south of the basin also produce water with higher temperatures above 150°C.
7) The typical well spacing (production well to injector) is 1 - 1.5 km horizontal distance at the top of the reservoir.

The typical well design consists of four sections. Two categories can be distinguished: Category 1, where the first section begins with 17.1/2” (13.3/8”) followed with 12.1/4” (9.5/8”), 8.5” (7”) and 6.1/8” (5”) bit and casing diameter; and category 2, where the first section begins with 23” or 26” (18.5/8” or 20”) followed by 17.1/2” or 16” (13.3/8”), 12.1/4” (10.3/4” - 9.5/8”) and 8.5” (7”) bit and casing diameter. Low clearance designs are less typical. Wells with desired flow rates above 90 l/s are typically designed with larger diameters (category 2). The first three sections are cased and cemented. The reservoir section is completed with a perforated liner assuring wellbore stability while allowing high flow rates and minimal pressure losses. The wells are typically deviated after the first section with a tangent section to the top of the reservoir. Within the reservoir, the inclination is often increased up to horizontal.

2. OBJECTIVE

SWM has set the goal of supplying their district-heating network with 80% of geothermal energy by 2040 (SWM, 2018). As suitable drilling locations in Munich and the vicinity are scarce and very expensive, the geothermal energy output of each drilling location must be maximized. Therefore, the well design and the exploration strategy must be adjusted to reach this goal. So far, the well design focused on minimizing cost and risk while providing a defined yield. “Keep it simple” was the guiding principle of many well designs. For future wells, maximizing the production per well site and minimizing the surface footprint will be the most important goal. To reach this, a range of measures is available, one of them being multilateral technology.

SWM is currently drilling a project with six wells (three geothermal doublets) in Munich. It will be the largest project in terms of energy output in the Molasse Basin and the largest low enthalpy hydrothermal project for district heating in Europe. At the end of this project, a multilateral exploration is to be realized and tested. Therefore, before drilling the multilateral branch, comprehensive studies must be performed to find the best technical option(s) to construct the multilateral well and to optimize the energy output. To decide which well is the best candidate for multilateral and where the well path should be directed to, a good understanding of the mechanisms of a multilateral production must be derived.

This paper provides the results of the feasibility study and describes the general concept of a multilateral well completion and whether productivity/injectivity can be improved cost-effectively. Additionally, the results of a reservoir simulation with different multilateral well path geometries are presented. The objectives are:

1) Determination of the technologies available and suitable for constructing a sidetrack in a geothermal well in the SGMB. This includes:
   a) Technical analysis of different completion options for the drilling and production phase
   b) Cost and risk analysis for different options
   c) Regulatory requirements

2) Determination and discussion of the theoretical potential of a multilateral well (a potential increase of productivity),
   a) based on analytical methods and
   b) a numerical reservoir simulation in a box model for various well path options.

3. AVAILABLE AND SUITABLE TECHNOLOGIES FOR A MULTILATERAL GEOTHERMAL WELL

In the drilling industry, technologies to drill and complete multilateral wells are available and used to:

a) access several reservoirs (production zones),
b) increase the contact area between the wellbore and formation and
c) reduce the environmental footprint. (Von Flatern, 2016)

Rudimentary multilateral (ML) wells have been used since the 1950s. By 1997 an industry group of operators formed a consortium (Technology Advancement of Multilaterals, TAML) and developed a classification system for ML wells. Accordingly, wells are categorized by the type of junction used to join the motherbore to the lateral in TAML Level 1 to 6. (Von Flatern, 2016)

The ascending order of this classification system reflects the increase of:

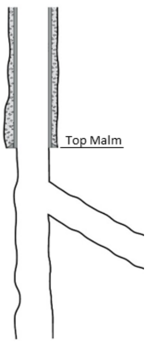
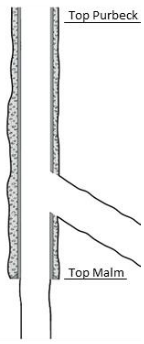
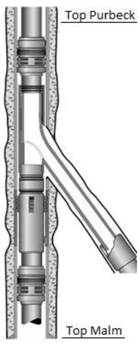
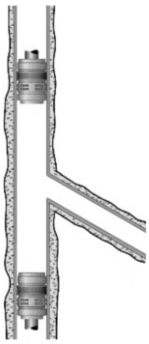
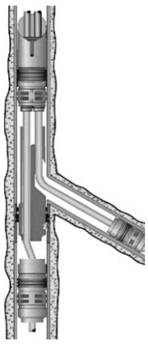
a) mechanical integrity,
b) pressure integrity,
c) technical complexity,
d) costs and
e) overall risks. (Von Flatern, 2016)

In the geothermal industry, multilateral wells have been used since the late 80ies, though on a much smaller scale than in the oil & gas industry. Detailed case studies are published, e.g., for the US (The Geysers; Henneberger et al., 1993), the Philippines (Tiwi and Bulalo; Stimac et al. 2010), Indonesia (Salak; Stimac et al. 2010; Peter et al. 2015), and Nicaragua (San Jacinto; Steffen et al. 2012).

3.1 Definitions of TAML Levels 1 - 6

A Level 1 multilateral is an open hole sidetrack either left barefoot or with an uncemented liner hung off in the open hole. The junction has no pressure integrity and no mechanical integrity. In a Level 2 junction, the lateral exits within a cased section of the motherbore. As in Level 1, the lateral is left barefoot, or a liner is hung off in the lateral's open hole. The junction still lacks pressure and mechanical integrity. For a Level 3 junction, the mechanical integrity is provided by a liner tied back into the previous casing while allowing flow from the motherbore. In Level 4, the lateral's liner is cemented, and access to the motherbore is established afterward. In addition to mechanical integrity, this type of junction makes the cementation of the liner feasible. However, neither Level 3 nor Level 4 provide pressure integrity. A further enhancement (Level 5) is achieved by installing packers and tubings, ensuring pressure integrity across the junction. In the most complex system (Level 6), the pressure integrity is attained by a single metal casing junction. However, this type is rarely used due to its complexity and many constraints. Table 1 shows a sketch of each multilateral level described above. (Hill et al., 2008; Von Flatern, 2016)

Table 1: Sketches of multilateral levels according to TAML (adopted from Von Flatern, 2016)

TAML Level	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Sketch						

3.2 Feasibility for Geothermal Wells in the South German Molasse Basin

As shown above, there are various levels of different junction types. The advantages and disadvantages of each level regarding its applicability in a typical well in the South German Molasse Basin (SGMB) are discussed in this section.

The following aspects are covered:

a) Feasible junction position in the motherbore
b) Applicable type of lateral completion
c) Mechanical support at the junction
d) Hydraulic isolation at the junction
e) Reduction of wellbore diameter due to installations
f) Costs
g) Permit risk
h) Re-entry capability and abandonment
i) Technical risks during production/injection

3.2.1 TAML Level 1:

A Level 1 multilateral can be drilled from the uncased section of the motherbore within the Malm reservoir at any position below the last production liner shoe set in the cap rock. None, one, or both boreholes can be completed (e.g., with perforated liner). However, even when completing both boreholes, one of the lateral completions must be hung off in the open hole section below the junction, leaving a part of the junction unsupported. The suitability for open-hole production depends on the local lithology: in some wells in the SGMB, the uppermost part of the open hole section is critical due to shaly layers in the transition zone between the reservoir and the cap rock. The technical risks during construction are considered moderate to high. Sealing off the motherbore and regaining access in the open hole is critical and prone to failures compared to operations in a cased hole. Re-entering the side branch is not guaranteed due to the junction in the open hole. The production is riskier than production from a junction in the cased hole, since formation instabilities are possible in this area. The costs of an open-hole sidetrack and Level 1 junction are the lowest compared to higher levels. Getting a permit is not critical for Level 1 as the lateral does not intersect other aquifers or reservoirs.

3.2.2 TAML Level 2:

A Level 2 junction can be drilled from the last production liner of the motherbore and placed in the Malm reservoir's cap rock. This area is the only feasible position due to the lack of hydraulic integrity of a Level 2 junction. Sidetracking at a shallower point could lead to the interconnection of different aquifers. The technical risks of the junction construction are lower compared to Level 1 as the packer or bridge plug, and the whipstock are placed within the cased hole. The lateral can be left barefoot or completed with a liner hung off in the open hole section below the junction. Either way, the junction is unsupported. Therefore, the formation's stability must be high. As discussed above, depending on the local lithology and the setting depth in the transition zone between reservoir and cap rock, shaly layers can interbed the more competent limestone rock. In this case, a Level 2 junction is not suitable. For re-entry into the lateral, a packer can be installed below the junction to allow, e.g., the installation of a lateral diverter. This will reduce the well's inner diameter, but the length of the narrower section is minimal, and the diameter reduction is minor, keeping the additional pressure losses small. The cost of constructing a Level 2 multilateral well is only marginally higher than a Level 1 junction. Getting a permit is not critical for Level 2 as the junction's position is in the cap rock above the reservoir, and the lateral does not intersect other aquifers or reservoirs.

3.2.3 TAML Level 3:

As for Level 2, the feasible junction position of Level 3 is within the cased hole section of the reservoir's cap rock. This is the only feasible position due to the lack of hydraulic integrity of the junction. Sidetracking at a shallower point could lead to the interconnection of different aquifers. The junction is mechanically supported and, in contrast to Level 2, formation instabilities at the junction during drawdown do not risk production. The risk of constructing a Level 3 junction is increased compared to Level 2. However, it is still lower than in Level 1. Like in Level 2, isolation equipment, such as packers or bridge plugs, and the whipstock are placed within the cased hole where setting and retrieval of these tools are less risky than in open hole. The re-entry into the lateral is possible by using diverters. Due to the tied-back completion, the junction's diameter is narrowed compared to a Level 2 junction. However, the reduction is not larger than with conventional perforated liner installations. The costs for Level 3 are increased but are at a moderate level compared to Level 4 to Level 6. Getting a permit is not critical for Level 3 if the junction's position is in the cap rock and the lateral does not intersect other aquifers or reservoirs than the Malm.

3.2.4 TAML Level 4:

The main attribute of a TAML 4 junction is a cemented lateral liner at the junction. However, the completions typically installed in the Malm reservoir are not cemented. Therefore, a Level 4 junction cannot be placed within the reservoirs' cap rock like Level 2 and Level 3. The junction can be positioned above the cap rock, but the lateral must then be separated into two sections: The first section is drilled, cased, and cemented to the top of the reservoir, and the second is drilled in the reservoir and completed with a perforated liner or left open hole. Theoretically, the branching could be placed far above the Malm reservoir in the Tertiary, allowing large distances to the motherbore. However, a Level 4 junction only has mechanical integrity, but hydraulic integrity is not achieved. Therefore, the integrity might not be sufficient to avoid communication between the Malm reservoir and the formation at or near the junction. Besides the lack of hydraulic integrity, the construction complexity is high and involves moderate to high risks. Additionally, the costs of a Level 4 completion are higher compared to a Level 3 junction. Finally, getting a permit is critical for this level due to the lack of hydraulic isolation. In conclusion, TAML Level 4 is not a suitable option.

3.2.5 TAML Level 5:

Like Level 4, this junction could be placed far above the reservoir in the Tertiary. In contrast to Level 4, hydraulic integrity is provided after the junction is completed. Therefore, well integrity is enhanced compared to Level 4, and the risk of communicating formations is reduced. However, the technical complexity as well as the costs and risks are high. Moreover, significantly diameter-constricting internals are installed, which generate pressure losses, impede passability, promote carbonate scaling and pose operating risks. However, a permit could be obtained for this option since hydraulic integrity is given. In conclusion, however, TAML Level 5 is not a suitable option.

3.2.6 TAML Level 6:

TAML 6 technology is not yet fully established and is hardly used in the oil and gas industry. Besides, this type of branching results in a significant reduction in both branches' diameter, which would create high-pressure losses compared to the conventional design and counteract the productivity increase achieved by adding a lateral. Finally, the costs and risks of the construction are high. TAML 6 is not a suitable option.

3.2.7 Summary:

In Table 2, a summary comparing each junction from TAML 1 to 6 is given. Level 1 is suitable for the application in the Malm but is not an optimal variant due to the increased risk during construction and production and the low re-entry capability. Level 2 is well suited for the application in the Malm and the preferred variant if the junction area is stable. Level 3 is also suitable and preferred if the junction area is not stable, although cost and risk are increased compared to Level 2. For both Levels, re-entry capability is provided, permit risk is low, and the wellbore diameter reduction is minor. For Level 2 and Level 3 junctions, the position of the multilateral junction is restricted to the top of the reservoir. Therefore, this junction position is used to discuss the potential increase of productivity in the following sections.

Table 2: Summary of the evaluation of multilateral junctions for geothermal wells in the SGMB.

TAML Level	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Position of the junction	In open hole Within reservoir	In cased hole Top of reservoir / cap rock	In cased hole Top of reservoir / cap rock	In cased hole Above cap rock	In cased hole Above cap rock	In cased hole Above cap rock
Lateral completion	Barefoot / Liner hung off or dropped in open hole	Barefoot / Liner hung off or dropped in open hole	Liner connected to cased hole - not cemented	Liner connected to cased hole - cemented	Liner connected to cased hole - cemented	Cased and cemented
Mech. support at the junction	No	No	Yes	Yes	Yes	Yes
Hydr. isolation at the junction	No	No	No	No	Yes	Yes
Reduction of wellbore diameter (in comparison to a unilateral completion)	None	None - Minor	Minor	Constrictions at the junction (diameter in aquifer not reduced)	Constrictions at the junction (diameter in aquifer not reduced)	Both branches constricted (alternative well design necessary, diameter in aquifer reduced)
Costs	Low	Low - moderate	Low - moderate	Moderate	High	High
Permit risk	Low	Low	Low	High (lack of zonal isolation)	Low	Low
Re-entry capability / Abandonment capability	Low	Low - High (Depending on system used)	Low - High (Depending on system used)	Low - High (Depending on system used)	Moderate - High	Moderate - High
Technical risks during construction	Moderate - High	Low	Low - Moderate	High	High	High
Technical risks during production/ injection	Low (if formation at junction or above is stable) High (if formation at junction or above is not stable)	Low (if formation at junction is stable) High (if formation at junction is not stable)	Low	High	Moderate	Low
Suitability for geothermal application in the SGMB	Moderate (if formation at junction is stable) Low (if formation at junction is not stable)	High (if formation at junction is stable) Low (if formation at junction is not stable)	High	Not suitable	Not suitable	Not suitable

4. THE THEORETICAL POTENTIAL OF A MULTILATERAL GEOTHERMAL WELL

4.1 Pressure Losses in a Unilateral Well

The overall pressure loss in a producing well can be divided into two components: the aquifer losses and the well losses. Aquifer losses occur in the aquifer rock, where the flow is laminar. They are time-dependent and vary linearly with the well discharge. Well losses occur in the near-wellbore region, completion, production casing, and tubing. Well losses are divided into linear and non-linear head losses. (cf. Langguth and Voigt, 2004; Kruseman and de Ridder, 2000)

Jacob (1947) gave the following equation to calculate the overall pressure losses:

$$s_w = (B_1 + B_2)Q + CQ^2 \tag{1}$$

where B_1, B_2, C and Q are linear aquifer-loss coefficient, linear well-loss coefficient, non-linear well-loss coefficient, and production rate. Rorabaugh (1953) suggested a slightly different version of equation (1):

$$s_w = (B_1 + B_2)Q + CQ^P \tag{2}$$

For P, values of 1.5 to 3.5 can be assumed, depending on the flow rate (see also Lennox, 1966). However, according to Kruseman and de Ridder (2000), a value of $P = 2$, as proposed by Jacobs (1947), is still widely accepted. This assumption has also been confirmed by well test analysis performed for geothermal wells in the Molasse Basin. Therefore, for all further discussions in this publication, a value of P = 2 is assumed. Based on the equation of Jacob (1947), an adaptation for the pressure losses in a producing low enthalpy geothermal well is here presented:

$$dp_w = (B_1 + B_2)Q + (C_{res} + C_{com} + C_{cas} + C_{tub})Q^2 \tag{3}$$

where B_1, B_2, C_{res} and Q are linear aquifer-loss coefficient due to the transmissibility of the reservoir, linear well-loss coefficient as a result of the skin, non-linear well-loss coefficient resulting from the turbulence flow at the entry into the borehole, and the friction losses of the open hole and production rate. $C_{com}, C_{cas}, C_{tub}$ are the friction loss coefficients due to the turbulence flow in the well completion, production casing, and production tubing.

All the non-linear well-loss coefficients can be summarized as the total non-linear well-loss coefficient C:

$$C = C_{res} + C_{com} + C_{cas} + C_{tub} \tag{4}$$

Table 3 illustrates the pressure loss components, including their occurrence, flow regime, and their calculation according to equation (3).

Table 3: Pressure loss components in a geothermal well producing water through a perforated liner, production casing, ESP, and production tubing.

Type of losses	Aquifer losses	Well losses							
Occurrence	Outside the near-wellbore region	Near-wellbore region and open hole section		Well completion	Well completion	Casing entry	Production casing	Pump intake	Production tubing
Linear / Non-linear	Linear	Linear	Non-linear		Non-linear		Non-linear		Non-linear
Pressure loss	B_1Q	B_2Q	$C_{res}Q^2$		$C_{com}Q^2$		$C_{cas}Q^2$		$C_{tub}Q^2$

In addition, well test analyses show that B_2 does not add significant linear well pressure losses (skin) after the well is stimulated with acid, a common procedure in the SGMB. Also, the holed section of the perforated liner does not contribute significantly to the overall well pressure losses. Therefore, in this study, it is assumed that all linear pressure losses in the well are caused by the aquifer losses, and the following simplification is made:

$$B_2 = 0 \tag{5}$$

$$B = B_1 \tag{6}$$

Therefore, the equation for the pressure losses used in this study is:

$$dp_w = BQ + (C_{res} + C_{com} + C_{cas} + C_{tub})Q^2 \tag{7}$$

and the equation for the production rate is:

$$Q = \frac{-B+(B^2+4C\ dp_w)^{0.5}}{2C} \tag{8}$$

Since this simplification has been made, it has to be considered that B is the result of two components: the reservoir transmissibility and the wellbore length within the pay zone (geometrical skin). Therefore, the B coefficient may vary even between wells of comparable reservoir transmissibility.

4.2 Pressure Losses in a Multilateral Well

4.2.1 Theoretical Discussion

For the theoretical discussion in this section, the following assumptions are made:

a) The lateral well has the same length, diameter, geometry, and completion as the motherbore (symmetrical branches).
b) There is no hydraulic contact between each branch during the drawdown. Therefore, the distance between the branches is larger than twice the drawdown radius of each branch.
c) The lateral starts at the top of the reservoir (position of the junction).
d) The reservoir is homogeneous and symmetric.
e) There are no additional pressure losses across the junction (e.g., installations with a smaller diameter).

For a multilateral well, the total flow Q in the motherbore above the junction must be the sum of all flows Q_i of the branches n below the junction to fulfill the mass balance:

$$Q = \sum_{i=1}^{n} Q_i \tag{9}$$

Assuming a homogeneous aquifer and identical multilateral branches, the flow in each branch is:

$$Q_i = \frac{Q}{n} \tag{10}$$

Therefore, using equation (7) and splitting the flow below the junction into n multilateral branches, the overall pressure losses are:

$$dp_w = \frac{BQ}{n} + \frac{(C_{res} + C_{com})Q^2}{n^2} + (C_{cas} + C_{tub})Q^2 \tag{11}$$

The aquifer losses and the well pressure losses below the junction of each branch are:

$$dp_{w\_below} = \frac{BQ}{n} + \frac{(C_{res} + C_{com})Q^2}{n^2} \tag{12}$$

The non-linear well pressure losses above the junction are:

$$dp_{w\_above} = (C_{cas} + C_{tub})Q^2 \tag{13}$$

Assuming two branches (*n=2*) the pressure losses are:

$$dp_w = \frac{BQ}{2} + \frac{(C_{res} + C_{com})Q^2}{4} + (C_{cas} + C_{tub})Q^2 \tag{14}$$

In conclusion, with one additional branch in the reservoir, the aquifer losses are halved. The non-linear well losses in the near-wellbore region and the completion up to the junction are quartered compared to a unilateral well with the same total flow rate. However, in this example, it is assumed that the branches' pressure drawdown radii do not intersect. This assumption is not realistic since the distance of the branches in the reservoir is limited due to the junction just above the reservoir. Consequently, a reduction of the aquifer losses in a realistic scenario will be reduced by a factor x:

$$dp_w = BQx + \frac{(C_{res} + C_{com})Q^2}{4} + (C_{cas} + C_{tub})Q^2 \tag{15}$$

In the best-case scenario, the pressure drawdown radii of the motherbore and the lateral do not intersect. In this case, the reservoir pressure losses are halved compared to a unilateral well with the same total flow rate (x = 0.5, as shown in equation (14)). In the worst-case scenario, the pressure drawdown radii of the motherbore and the lateral fully intersect. In this case, the drainage area within the reservoir is not enlarged by the lateral. Therefore, the pressure losses in the reservoir stay the same compared to a unilateral well with same total flow rate (x = 1). For any case between these two extremes, x will be between 0.5 and 1:

$$\frac{1}{2} < x < 1 \tag{16}$$

Unlike the reduction of the aquifer losses, the reduction of the non-linear well losses below the junction is not as sensitive regarding the distance of the wells. They will quarter even if the multilateral branches will be drilled in a shorter distance to each other. The non-linear well losses below the junction are caused by friction pressure losses in the open hole section, in the completion up to the junction, and in the near-wellbore region. They all occur either immediately in or in close vicinity to the well, assuming ideal radial flow.

To illustrate this, Figure 3 shows the flow velocity in the near-wellbore area relative to the maximum flow velocity at the borehole wall calculated with the following formula:

$$v_{rel} = v / v_{max} = \frac{Q}{r^2 L\pi} / \frac{Q}{r_w^2 L\pi} = \frac{r_w^2}{r^2} \tag{17}$$

where v, v_{max}, Q, L are the flow velocity at the radial distance r to the wellbore axis, the flow velocity at the wellbore wall, the flow rate produced by the well, and the length of the wellbore.

It illustrates the rapid decrease of flow velocity with increasing distance to the well. Practically, the second branch will be out of this near-wellbore zone. As a result, non-linear well losses will quarter with a second branch drilled outside the near-wellbore zone.

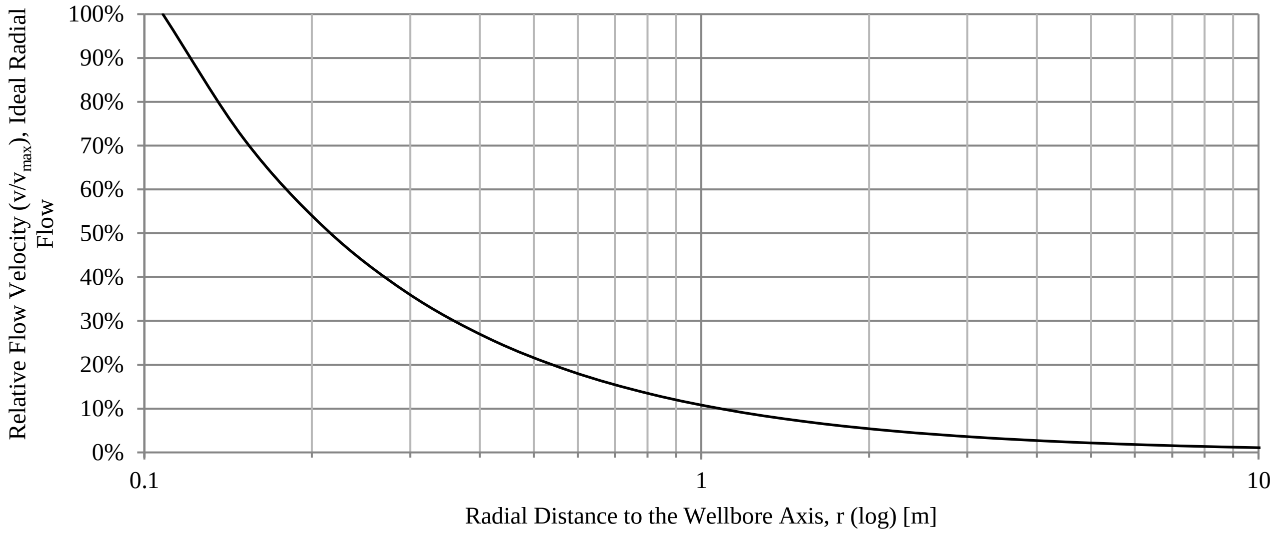


Figure 3: Relative flow velocity (*v/v$_{max}$*) at a radial distance to the wellbore axis. Wellbore diameter = 8.1/2"

4.2.2 Numerical Simulation - Reduction of the Aquifer Losses

As shown in the previous section, the aquifer loss can be reduced by 0 to 50% due to the second branch. There is no reduction of the aquifer loss if the second branch is drilled next to the motherbore. In this case, the drainage radius in the aquifer is the same compared to a unilateral well. There is a reduction of 50% if the second branch is drilled with the same geometry (inclination, length within the pay zone) at a large distance to the motherbore where no hydraulic contact between the pressure drawdown radii of the branches occurs. Not only the distance between the branches is relevant, but also the length of the multilateral branch will influence the total reduction in aquifer loss. A vertical and short branch will lead to lower reduction than a high inclination branch with a high length in the pay zone. This applies to unilateral and multilateral exploration.

To quantify the aquifer loss, a numerical simulation was performed. Figure 4 shows the well paths created as the basis for the numerical reservoir simulation. The motherbore is illustrated in purple. Multilateral options are designed with different inclinations of 0°, 19°, 38°, 56°, and 75° in the colors pink, turquoise, green, yellow, and red and different azimuths of 90°, 70°, 45°, 20°, and 0°. The motherbore has an inclination of 75° and an azimuth of 90°.

Table 4 shows numerical parameters of the motherbore and the multilateral well paths. The motherbore is based on the plans of one of the wells currently under construction in Munich. The dogleg severity (DLS) of the multilateral wells is higher than in the motherbore to achieve distance as fast as possible. The total depth of 2841 m TVD is the same for all well path and is the base of the reservoir. According to the inclination and azimuth of the multilateral branch, the distance to the motherbore and the length within the reservoir section varies widely.

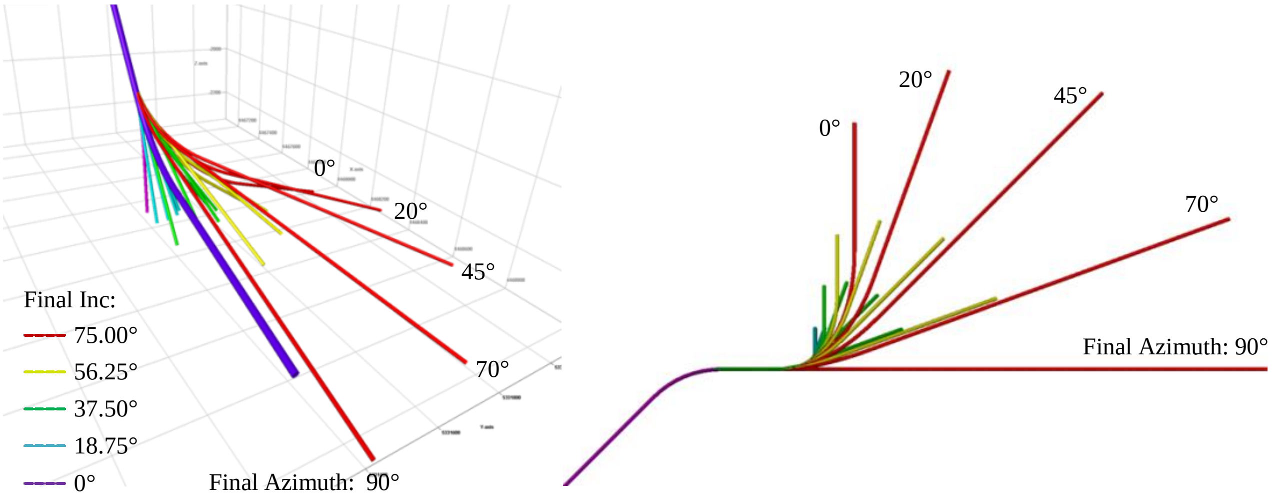


Figure 4: Multilateral well paths for numerical reservoir simulation. Multilateral options with inclinations of 0°, 18.75°, 37.50°, 56.25°, and 75° and azimuths of 90°, 70°, 45°, 20° 0°.

Table 4: Well path data of the motherbore and multilateral options

Motherbore (MB), multilateral option number	Final inclination [°]	Final azimuth [°]	Dogleg severity of the build section after the junction [° / 30 m]	Total depth [m MD]	Total depth [m TVD]	Distance between the motherbore and the multilateral branch at total depth [m]	Length within the reservoir [m]
MB	75.00	90	3.5	3741	2841	0	1082
1	75.00	90	4.5	3972	2841	263	1313
2	75.00	70	4.5	3945	2841	416	1286
3	75.00	45	4.5	3845	2841	716	1186
4	75.00	20	4.5	3684	2841	937	1025
5	75.00	0	4.5	3516	2841	1006	857
6	56.25	90	4.5	3389	2841	369	730
7	56.25	70	4.5	3380	2841	450	721
8	56.25	45	4.5	3352	2841	645	693
9	56.25	20	4.5	3307	2841	811	648
10	56.25	0	4.5	3259	2841	894	600
11	37.50	90	4.5	3175	2841	662	516
12	37.50	70	4.5	3174	2841	685	515
13	37.50	45	4.5	3170	2841	749	511
14	37.50	20	4.5	3164	2841	835	505
15	37.50	0	4.5	3153	2841	885	494
16	18.75	90	4.5	3108	2841	805	449
17	18.75	70	4.5	3108	2841	811	449
18	18.75	45	4.5	3109	2841	834	450
19	18.75	20	4.5	3110	2841	865	451
20	18.75	0	4.5	3108	2841	889	449
21	0	90	4.5	3092	2841	892	433

The numerical simulation was performed in the following steps with the software package Petrel/Eclipse^{TM}:

1) Generation of a simplified grid (layer cake model) considering the geological model
2) The Malm reservoir is assumed to be 370 m thick and of homogeneous permeability and porosity
3) Implementation of the motherbore and the multilateral wellbore options (1 unilateral scenario, 21 multilateral scenarios)
4) The step-drawdown test with 5 steps (15, 30, 60, 100 and 120 l/s), 6 months duration each to reach steady state conditions, was simulated for various permeabilities for each multilateral option. Twenty different permeability values between 2.42 and 300 mD have been assumed, based on well test analyses of geothermal wells in the Molasse Basin. Consequently, 440 step-drawdown tests have been simulated in total. The maximal allowable pressure drawdown in the well was limited to 100 bar.
5) Determination of the linear aquifer-loss coefficient B for each stage and the mean value of B for the total step-drawdown test

In Table 5, the results of the numerical simulation are listed. Following the previous theoretical discussion, the reduction lies between factors 0.5 to 1. In general, the simulation shows that the reduction of the B coefficient increases with decreasing permeability. This effect results from the larger pressure drawdown radius and higher interaction between the branches for higher permeabilities. Moreover, the best results show the options with the highest inclination in the reservoir due to the lowest geometrical skin. Even for closely located wellbores (e.g., option 1), the reduction is still high due to the length of the multilateral branch. However, the best results show options with high lengths in the reservoir combined with a large distance between the branches (e.g., options 2, 3, and 4).

In this simulation, the motherbore has a high inclination and a high length within the pay zone. If the motherbore would be vertical and the multilateral branch would be highly inclined, the reduction of the aquifer losses could be higher than 50% ($x < 0.5$). However, it is common to drill with high inclination through the reservoir in all wells. Therefore, the assumption of a vertical motherbore is not part of this study. Moreover, the reduction of the aquifer loss could also be higher than 50% if the reservoir is not homogeneous and the multilateral branch hits a target with higher transmissivity. However, the influence of the spatial distribution of reservoir characteristics is not evaluated in this study.

Table 5: Numerical simulation results for the reduction of the linear aquifer loss using a multilateral (linear aquifer loss of the multilateral [motherbore + lateral] / linear aquifer loss of the unilateral [motherbore]).

Option Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Final Azimuth	90°	70°	45°	20°	0°	90°	70°	45°	20°	0°	90°	70°	45°	20°	0°	90°	70°	45°	20°	0°	90°
Final Incl. / k [mD]	75°					56°					38°					19°					0°
2.4	0.71	0.66	0.65	0.66	0.70	0.86	0.81	0.78	0.77	0.78	0.86	0.84	0.82	0.82	0.82	0.85	0.85	0.84	0.84	0.84	0.85
5.2	0.72	0.68	0.66	0.68	0.72	0.87	0.82	0.79	0.79	0.79	0.87	0.85	0.83	0.83	0.83	0.86	0.85	0.85	0.85	0.85	0.86
11.1	0.74	0.70	0.69	0.70	0.74	0.88	0.83	0.80	0.80	0.81	0.88	0.86	0.84	0.84	0.84	0.87	0.87	0.86	0.86	0.86	0.87
23.7	0.76	0.72	0.71	0.72	0.75	0.89	0.84	0.82	0.81	0.82	0.89	0.87	0.85	0.85	0.85	0.88	0.87	0.87	0.87	0.87	0.88
50.8	0.77	0.73	0.72	0.73	0.76	0.89	0.85	0.82	0.82	0.83	0.89	0.87	0.86	0.85	0.85	0.88	0.88	0.87	0.87	0.87	0.88
108.8	0.77	0.74	0.73	0.74	0.77	0.90	0.85	0.83	0.82	0.83	0.89	0.88	0.86	0.86	0.86	0.88	0.88	0.88	0.88	0.88	0.88
300.1	0.78	0.74	0.73	0.74	0.77	0.90	0.85	0.83	0.83	0.83	0.89	0.88	0.87	0.86	0.86	0.89	0.88	0.88	0.88	0.88	0.89

5. CONCLUSIONS

The technical analysis regarding the applicability of different technical junction designs for geothermal projects shows that Level 2 and Level 3 junctions are best suited for the application in the Malm reservoir. Level 2 is the preferred variant if the area at the junction is stable. Level 3 is the preferred variant if the area at the junction is not stable. As only Level 2 and Level 3 junctions are well suited, the position of the multilateral junction is restricted to the top of the reservoir or the cap rock. Level 1 is possible but is not an optimal variant due to the increased risk during construction and production and the lower re-entry capability.

The assessment of the theoretical potential of a multilateral geothermal well shows that with one additional branch in the reservoir, the aquifer losses are halved, while the non-linear well losses in the near-wellbore region and in the completion up to the junction are quartered compared to a unilateral well with same total flow rate. This reduction is valid if the pressure drawdown radii of the branches do not intersect with each other. For the analysis, a homogeneous and symmetric reservoir was assumed, with a lateral of the same length, diameter, geometry, and completion as the motherbore (symmetrical branches) starting at the top of the reservoir (position of the junction). Moreover, no additional pressure losses across the junction are considered.

To quantify the aquifer loss for the case of intersecting pressure drawdown radii and different lateral geometries in the reservoir, a numerical simulation was performed. In general, the simulation shows that the reduction of the aquifer losses increases with decreasing permeability. This effect results from the higher interaction between the branches for higher permeabilities. Moreover, the best results are achieved by laterals with high inclination and high length in the reservoir since the drainage area is maximized. However, the best results show options with high lengths in the reservoir combined with a large distance between the branches. For well paths with these properties, the simulation shows a reduction of the overall aquifer losses by a factor of 0.65 to 0.73 compared to a unilateral well, depending on the reservoir permeability.

6. OUTLOOK

The outcome of this study is the basis for further detailed analysis and a first multilateral test well, which is drilled and tested in 2020 in Munich. The further steps are:

1) Detailed planning of multilateral options Level 2 and Level 3
2) Well targeting based on a detailed and calibrated reservoir model → Decision which well of the project is the ideal candidate for the first multilateral
3) Final technical and economic assessment
4) Final technical planning of the drilling and testing of the multilateral
5) Drilling and testing of the multilateral branch in one of the six wells of the drilling project.
6) Technical and economic analysis of the drilling and well testing data → Conclusions and recommendations for further wells in the basin and reassessment of multilateral use

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