Chair of Economic- and Business Management

Master's Thesis

A techno-economic assessment of the conversion of existing oil and gas workover rigs for geothermal projects

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Task

Mr. Jakob Krocker will discuss the topic

A techno-economic assessment of the conversion of existing oil and gas workover rigs for geothermal projects

for processing in a master's thesis.

In a theory section, the techno-economic fundamentals of geothermal heat extraction will be explained in detail. This includes a comprehensive introduction to the technical fundamentals of geothermal heat extraction with a view to the applicability of proven workover rigs of the oil and gas industry in the field of geothermal energy. In addition, the legal framework at the inter-/national level will be presented and the basic business concepts that are relevant for the further analysis are explained.

Building upon this, a comprehensive techno-economic analysis for the conversion of a Confind AM12/50 for potential geothermal applications is carried out in a practical part of the work. In the course of this, a case study of this conversion process will be carried out in as much detail as possible, in which the basic economic feasibility as well as meaningful KPI will be worked out using information from a project partner. This part will be supplemented by ta comprehensive market study for the countries Austria and Germany, in which opportunities and potentials with regard to the more comprehensive roll-out of this idea will be analysed.

Leoben, November 2022

Univ.-Prof. Dr. Wolfgang Posch

Lehrstuhl für Wirtschafts- und Betriebswissenschaften

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Acknowledgement

Great thanks go to Dipl.-Ing. Dr. mont. Stefan Wirth without whose support this thesis would not have been possible. Together with him, the topic and the content of the thesis were determined. However, his support went far beyond supervising the work. Not only did he enable me to go on some very informative and exciting excursions, but he also brought me into contact with very interesting personalities. In addition to his competence, I appreciate him above all for his friendly, down-to-earth, and generous way of dealing with me.

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Abstract

In this thesis, the conversion of oil and gas equipment, namely a workover rig, for geothermal purposes is discussed. Precisely, the converted rig should be able to perform geothermal drilling. Thereby, the focus is on the question of whether the conversion is economically feasible and strategically wise. For this, on the one hand, the conversion itself must be examined, on the other hand, it is also necessary to take into account the general development of geothermal energy.

Actually, it is the emerging development of geothermal energy in Europe and the increasingly difficult conditions in the European oil and gas industry that have led to this thesis. In countries like Austria and Germany, geothermal energy is supposed to be developed extensively in the next few years. Reasons for this trend are the intention to establish a more sustainable energy mix and the intention to obtain more independence in regard to energy supply. Due to the transition towards more sustainable energy sources, the production of fossil energy is retrogressive and oil and gas companies in central Europe are facing a very tough and challenging future. These companies are under pressure, thus, are obliged to make strategic decisions. The application of oil and gas equipment for geothermal purposes is a possible strategic change of course. Especially, because the central European geothermal drilling industry urgently needs machinery, labor, and know-how to be able to realize the planned comprehensive development of geothermal energy.

If the regarded oil and gas rig were a drilling rig, it could be used for geothermal drilling without any difficulties. However, since the rig is a workover rig, it is actually incapable of drilling and needs to be supplemented by some additional systems to change that. In the course of this thesis, these systems and their according acquisition costs are identified so that, finally, the conversion costs can be determined. However, the determination of the investment´s extent is only one part of the economic feasibility study. In addition, it must also be determined whether the operation of the converted rig and the services that can be offered with the converted rig are competitive. From a technical point of view, it can be anticipated that the converted rig will able to drill to depths of up to 800 meters, thus medium-deep wells. Compared to the shallow drilling and deep drilling industry, medium-deep drilling industry is more of a niche industry with relatively few players. On one side, the sparse competition can be seen as an advantage, on the other side, the medium-deep drilling market presents hurdles that must be overcome in order to be successful.

Finally, this thesis provides information about the profitability of the conversion and presents recommendations for action and possible solutions.

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ABGB	Allgemeines Bürgerliches Gesetzbuch
BOP	Blowout preventer
C	Celsius
CAPEX	Capital expenditures
CF	Cash flow
Cm	Centimeter
DTH	Down-the-hole drilling
EBIT	Earnings before interest and taxes
EBITDA	Earnings before interest, taxes, depreciation and amortization
GRT	Geothermal Response Test
GW	Giga Watt
GWh	Gigawatt hour
HP	Horse power
HSE	Health, safety, and environment
kg/m^3	Kilogram per cubic meter
km	Kilometer
Km/h	Kilometers per hour
KPI	Key performance indicator
kW	Kilo Watt
mm	Millimeter
m/s^2	Meter per square second
m^3/s	Cubic meter per second
MW	Mega Watt
mW/m^2	Milli Watt per square meter
OPEX	Operating expenses
PJ	Peta Joule
ROI	Return on investment
TD	Target depth
TJ	Terajoule
TWh	Terawatt hour
W	Watt
WKO	Wirtschaftskammer Österreich
w.rd.	Without release date

1 Introduction

In this chapter, it is briefly presented which subjects this thesis covers and what objective it pursues. However, at the beginning, I want to explain my motivation and the circumstances under which this thesis came about.

This thesis unites two different energy industries. On the one hand, the long-established and powerful oil and gas industry and, on the other hand, the smaller but ambitious geothermal energy industry. A very interesting constellation, which can also be found in the choice of my studies. I finished my bachelor´s degree in Petroleum Engineering and then continued with a master´s degree in Management and Business Administration with a focus on geothermal energy. One reason why I started studying Petroleum Engineering is that I was impressed, and still am, by the process of drilling hundreds or even thousands of meters into the earth. Nevertheless, I wanted to head into a more future-oriented and sustainable direction when I started my master's degree. For me, it is all the better that I can now combine the topics of drilling and geothermal energy in this thesis. This opportunity arose when I met Dipl.-Ing. Dr. mont. Stefan Wirth, HSEQ Director of Christof Industries Global GmbH. Because CMB Well Services S.R.L., a joint venture of Christof Industries Global GmbH and MB Well Services GmbH which is operating in the oil and gas industry in Romania, is looking for innovative application opportunities for their workover rigs. Thus, Dipl.-Ing. Dr. mont. Stefan Wirth assigned me to investigate the question if conventional oil and gas workover rigs can be used for geothermal drilling projects.

1.1 Initial situation and problem

The title of this master´s thesis, namely "A techno-economic assessment of the conversion of existing oil and gas workover rigs for geothermal projects" reveals that on the one hand, this thesis is about the changeover of existing machinery for a new field of application, however, on the other hand, it deals with the transition from fossil energy sources towards sustainable and renewable energy sources. The transition towards sustainable and renewable energy sources is crucial for accomplishing the Paris Agreement, which sights to limit the increase in global average temperatures to less than 1.5°C above pre-industrial levels by reducing and, eventually, eliminating greenhouse gas emissions.

However, it is not only climate change but also the increasing global energy demand based on population growth and economic development that confronts the energy industry with major challenges. Furthermore, recent global events such as the COVID-19 pandemic and the Ukrainian conflict raised the quest for energy security and independence. To be able to take all these hurdles urgently requires the comprehensive development of alternative energies. Since geothermal energy is a clean, reliable, and widespread source of heat and electricity, it can play an essential role in the future energy mix alongside other renewable energy sources.

Despite the potential of geothermal energy being known by most stakeholders, its global usage is relatively underdeveloped compared to, for instance, wind or solar energy. One reason is the inability to produce it because of insufficient machinery, personnel, and know-how.[1]

1.2 Objective and research focus

As mentioned above, among other reasons, the lack of machinery and personnel is responsible for the inadequate development of geothermal energy. Within this thesis, the focus is on a possible solution to this problem. Concretely, the changeover of existing oil and gas equipment for geothermal purposes is assessed. This idea is not far-fetched because both resources, hydrocarbons and geothermal heat, reside in the subsurface and need to be tapped by drilling into the ground. The process of drilling is almost the same, no matter if the reservoir to be drilled into contains hydrocarbons or geothermal heat. Hence, it is common practice that drilling companies use their drilling rigs for oil and gas projects as well as for geothermal projects.

However, in the context of this thesis, the transformation of so-called oil and gas workover rigs for geothermal purposes is examined. Workover rigs are mainly used in the oil and gas industry to maintain and optimize existing wells, so drilling is not their intended use. Therefore, a transformation is required to enable workover rigs to drill a well. This transformation is at the center of this thesis.

The assessment of the rig transformation has two components, a technical one and an economical one. For each component, two subordinated questions emerge:

- What modifications are necessary and are they technically feasible?
- What are these modified workover rigs technically capable of, especially, how deep can they drill?

- What costs are caused by these modifications and what does it cost to operate with a converted rig?
- Is there a target market for converted rigs?

The answers to these questions are elaborated and should assist in making a final statement, which is the objective of this thesis. This final statement should declare if the transformation of workover rigs for geothermal purposes is economically feasible.

1.3 Methodical approach

The thesis is constructed in a way that in the end, a recommendation regarding the conversion can be made. To be able to make such a statement two different subject areas need to be analyzed. On the one side, it is necessary to assess the actual and

[1] Refer to International Renewable Energy Agency and International Geothermal Association (2023), page 8 pp.

future situation of geothermal energy and its market. On the other hand, the changeover process of the workover rig must be discussed.

For the assessment of geothermal energy´s potential, two different roadmaps are consulted. One roadmap deals with the Austrian future concerning geothermal energy and was published by Austria´s Ministry of Climate Protection, Environment, Energy, Mobility, Innovation, and Technology. The other roadmap discusses the geothermal future in Germany and was published by a prestigious institution called "Fraunhofer-Einrichtung für Energieinfrastrukturen und Geothermie IEG". Mainly, it is pointed out to which extent geothermal energy can contribute to the future energy mix and what needs to be done to optimize the usage of geothermal energy.

When it comes to the conversion of the workover rig, first, the technical frame conditions need to be determined. Therefore, several experts are consulted, which have long-lasting experiences in the drilling sector. With the assistance of these experts, the necessary technical modifications are identified. For the identification of the costs regarding the changeover and the costs of operating with the converted rig, again, professionals from the drilling business are consulted. To be able to analyze the computed costs and put them into context, different economic, financial, and strategic methods are applied. Selected KPIs are calculated to investigate if drilling with a converted rig is economically feasible, a sensitivity analysis regarding the CAPEX and OPEX is conducted and a Gedankenexperiment towards a more sustainable drilling rig is performed. A very expressive and decisive method that is executed in the course of the thesis is a market analysis concerning the drilling market in Austria and Germany. This analysis is supposed to give answers concerning the question, of whether there is a market for the converted rig. Finally, the thesis is completed by the conclusion including a statement regarding the feasibility of the conversion.

1.4 Structure of thesis

The thesis is divided into two parts, the theoretical part, and the practical part. In the theoretical part the basic knowledge, regarding all subjects that are processed in the practical part, is established. The theoretical part is structured as follows.

In the beginning, geothermal energy is explained in a very general way. It is explained where it comes from and where it can be found. Additionally, the different forms of geothermal energy applications are listed and briefly explained in how they function. Next, an overview is given of the current status of geothermal energy usage and its potential for the future. When discussing the status quo and the future outlook, the focus is on Austria and Germany, however, also a global overview is provided. The next subject that is theoretically covered is the process of drilling and the required equipment to drill. To be able to understand the transformation process of a workover rig, which is covered in the practical part, it is necessary to explain the drilling equipment a bit more in detail. Especially, for the drilling process the legislative framework is of interest. Therefore, the different national legislations in force that need to be observed when drilling in Austria and Germany are introduced. The last chapter of the theoretical part deals with the presentation of economic and financial methods to determine the profitableness of the transformation process.

The practical part commences with a short introduction to workover and workover rigs. Subsequently, the changeover process of a workover rig into a drillable rig is presented. First, the technical aspects of the changeover process are highlighted. Based on a particular type of workover rig, it is explained which additional equipment is required and why it is required. Next, the financial aspects of the changeover process are discussed. The costs that generate in the course of the changeover are calculated and, additionally, it is investigated what the realization of drilling projects with the converted rig costs. To be able to further analyze and evaluate the results in the cost calculations, different economic, financial, and strategic methods are applied. Namely, these are the calculation of KPIs, a sensitivity analysis, a Gedankenexperiment towards a more sustainable drilling rig, a market analysis of the Austrian and German drilling market, and an analysis of medium-deep drilling. Finally, a conclusion is performed that should clearly state, if the changeover of a workover rig is economically feasible.

2 Theoretical part

Within the course of the theoretical part, different subjects are covered in such a way that the content of this thesis´ practical part can be understood without difficulties. Presented in the theoretical part is an overview of geothermal energy including its exploration, its production, its forms of usage, its legal frame, its status quo of usage, and its potential. Furthermore, procedures and instruments for economic evaluation, which are conducted in the practical part, are introduced.

2.1 Geothermal energy

Geothermal energy is thermal energy, thus heat, that is developed and stored within the subsurface of planet Earth. The term “geothermal“ composes of the two Greek words “geo” and “thermos”. “Geo” stands for earth, while “thermos“ refers to hot or warm. Geothermal energy can derive from three different sources. These are residual heat of the time when the planet formed and accreted, frictional heat from dense core material sinking to the center of the earth, or heat from the decay of radioactive elements.[2] However, the majority of the subsurface heat comes from the decay of radioactive material like Potassium or Thorium. Radioactive decay is a continual process within the earth´s core, where temperatures can reach more than 5.000°C. This enormous heat radiates from the core and heats its encircling layers which are displayed in Figure 1. Generally, it can be said that temperature increases towards the earth´s core, so the earth´s core is its hottest zone.[3]

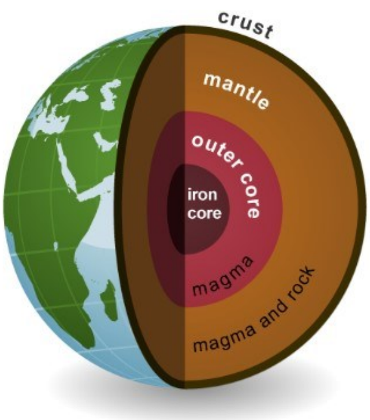

Figure 1: Interior of the earth[4]

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[2] Refer to Think Geo Energy, https://www.thinkgeoenergy.com/geothermal/what-is-geothermal-energy/ (accessed: 09.02.2023)
[3] Refer to National Geographic, https://education.nationalgeographic.org/resource/geothermal-energy (accessed: 09.02.2023)
[4] Source: U.S. Energy Information Administration, https://www.eia.gov/energyexplained/geothermal/ (accessed: 09.02.2023)

To give an idea about the different layer´s dimensions it can be mentioned that the core, existing of an inner and an outer part, has a radius of around 3.620 kilometers and the mantle has a thickness of around 2.895 kilometers. Temperatures within the mantle increase from around 200°C at the mantle-crust boundary to around 4.000°C at the mantle-core boundary. The earth´s crust consists of two forms of tectonic plates, the continental plates that have a thickness between 24 and 56 kilometers and the oceanic plates being 4,8 to eight kilometers thick.[5] The temperature of the crust solely depends on the crust´s plates and varies significantly between different areas, countries, and continents. In total, the crust exists of eight major tectonic plates and where they meet, the heat can be found closer to the surface and is often revealed in the form of geysers, hot springs, or volcanic activities.[6]

The described increase in temperature with increasing depth is expressed by the geothermal gradient. Globally, this geothermal gradient averages out at 30°C of temperature increase per kilometer depth and can vary between 20°C and 50°C per kilometer. However, this average value is not very meaningful because the value strongly fluctuates. Figure 2 presents a map of Europe with differently colored areas representing a different magnitude of geothermal gradient. The red areas are the ones with the highest gradient, whereas the blue areas possess the lowest gradients.

Figure 2: Geothermal heat map of Europe[7]

[5] Refer to U.S. Energy Information Administration, https://www.eia.gov/energyexplained/geothermal/ (accessed: 09.02.2023)
[6] Refer to Think Geo Energy, https://www.thinkgeoenergy.com/geothermal/what-is-geothermal-energy/ (accessed: 09.02.2023)
[7] Source: Askja Energy, https://askjaenergy.com/2012/09/ (accessed: 09.02.2023)

Geothermal potential cannot only be expressed with the geothermal gradient but also with the natural heat flux. The natural heat flux is given in milliwatts per square meter and the higher it is, the more heat can be transferred by a particular formation. Globally, the average natural heat flux amounts to 70 mW/m^2. For illustration, a heat flux of 70 mW/m^2 means that with the geothermal energy present in the area of a football pitch, a typical radiant heater can be powered.[8] In Figure 3, the varying natural heat flux of Austria is depicted. Obviously, the eastern part of Austria, the north-western part of Upper Austria, and an area in the Austrian Alps possess a natural heat flux that is above the global average value.

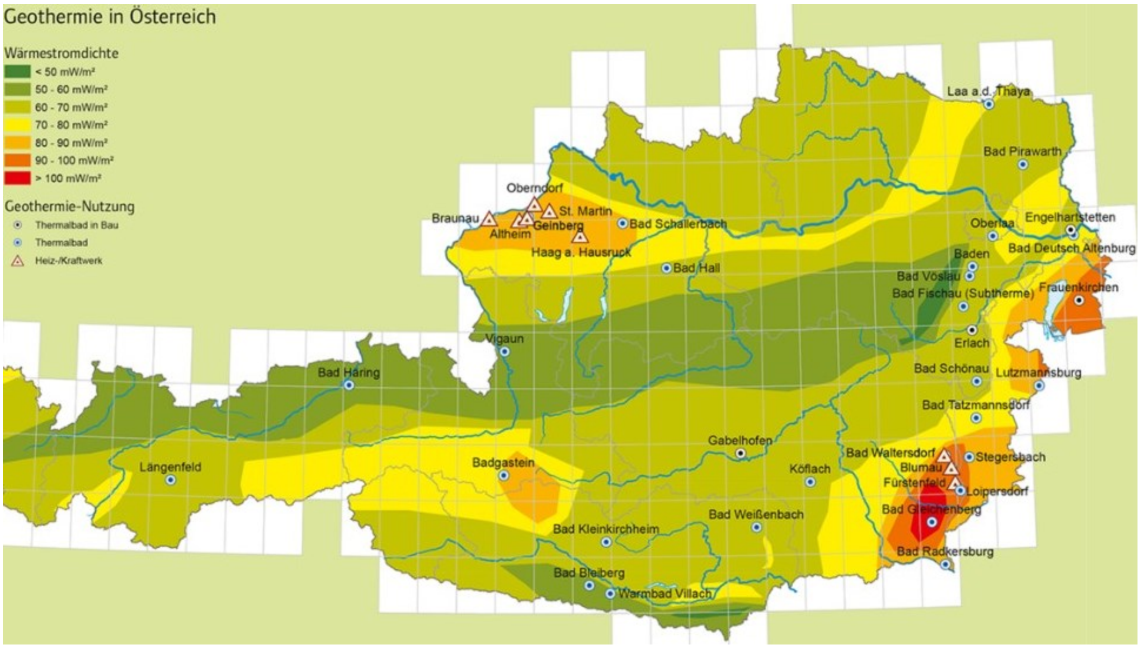

Figure 3: Natural heat flux in Austria[9]

Especially, regions with a relatively high geothermal gradient, respectively a relatively high natural heat flux, are interesting for making use of the available geothermal energy. This is because heat can be found in low depths or even at the surface. Therefore, when regarding Figure 2, it is not surprising that the historically predominant areas with geothermal energy utilization, for instance, can be found in Italy or Iceland.

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[8] Refer to Gregor Götzl, Geologische Bundesanstalt, https://projects-gba.geologie.ac.at/s/Rjf9LT9ABT4SsRj (accessed: 09.02.2023)

[9] Source: Geologische Bundesanstalt, https://www.geologie.ac.at/forschung-entwicklung/kartierung-landesaufnahme/energie/geothermie/ (accessed: 09.02.2023)

2.1.1 Forms of geothermal energy usage

There are two different forms of making use of geothermal energy, its direct use and its use for power production. For both usages, it is necessary to establish a transition from the surface to the subsurface geothermal reservoir.[10]

Direct or non-electric use refers to the immediate utilization of a fluid tempered by geothermal energy for heating and cooling applications. Historically, people used hot springs for bathing and cooking amongst other utilization. Nowadays, examples of direct use are space heating and cooling, heating of swimming pools and baths, agricultural greenhouse heating and crop drying, and providing heat and cold for industrial processes and heat pumps.[11] Most direct use applications can be applied for geothermal reservoirs with temperatures ranging from 20°C to 120°C. In general, two types of direct geothermal energy utilization can be distinguished. One option is an open loop system where hot geothermal fluids from water-based geothermal reservoirs, so thermal reservoirs, are extracted and used for heating purposes. The other option is to install a closed system of pipes and wells in the subsurface. A fluid circulates in such a system that heats up in the underground due to heat conduction. At the surface, it is then used either directly as heat or through heat pumps.[12] This working principle is further discussed in Chapter 2.1.2. A special form of direct use, which should at least be mentioned in this context, is the extraction of minerals from geothermal brines. Minerals like lithium, silica, zinc, manganese, several rare earth elements and many other elements can be extracted from geothermal brines and used commercially. However, this form of use plays no further role in this thesis.[13]

When it comes to the indirect use of geothermal energy, the production of electricity is meant. For that matter, hot fluids from underground reservoirs are drawn to the surface via a well. At the surface, steam is produced with the help of the hot fluids. The steam then powers turbines that generate electricity. In general, three main types of geothermal power plant technologies exist, namely the dry steam power plant, the flash steam power plant, and the binary cycle power plant.

At a dry steam plant, the extracted fluid is mostly steam, so it can directly be drawn to a turbine. The turbine then drives a generator that produces electricity. After the steam condenses, it is reinjected into the subsurface reservoir, as Figure 4 shows.

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[10] Refer to Think Geo Energy, https://www.thinkgeoenergy.com/geothermal/what-is-geothermal-energy/ (accessed: 09.02.2023)
[11] Refer to National Institute of Building Sciences, https://wbdg.org/resources/geothermal-energy-direct-use (accessed: 10.02.2023)
[12] Refer to Think Geo Energy, https://www.thinkgeoenergy.com/geothermal/geothermal-energy-production-utilisation/ (accessed: 14.02.2023)
[13] Refer to International Renewable Energy Agency and International Geothermal Association (2023), page 24

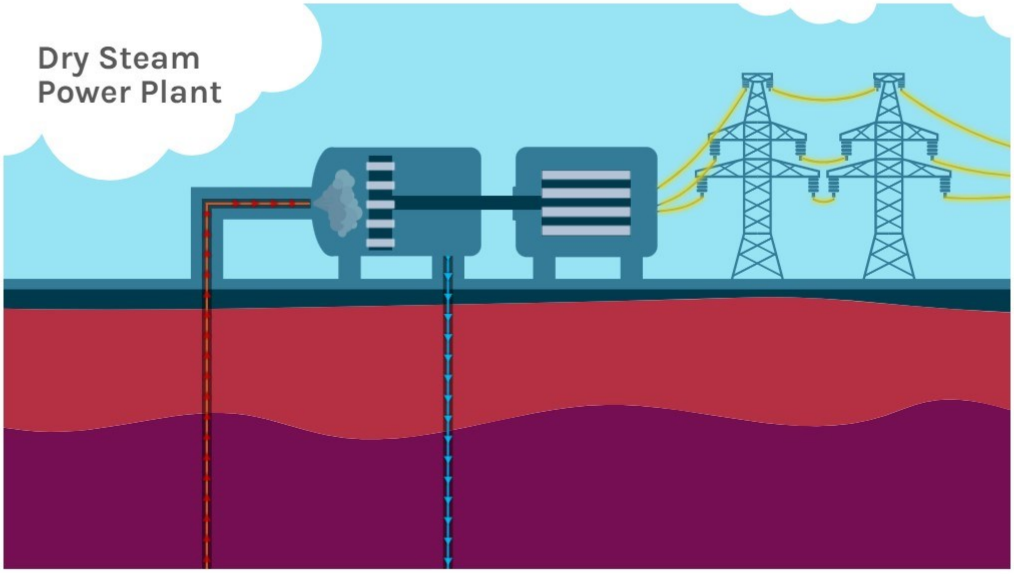

Figure 4: Dry steam power plant[14]

Flash steam power plants, nowadays, are the most common type of geothermal power plants. Liquids with temperatures above 182°C are transported to the surface under high pressure. At the surface, the hot liquid enters a low-pressure tank and this change in pressure allows some of the liquid to rapidly transform, or "flash," into steam. The steam then drives a turbine, which in turn powers a generator, condenses into a liquid phase, and is eventually reinjected. The working principle of a flash steam power plant is presented in Figure 5.

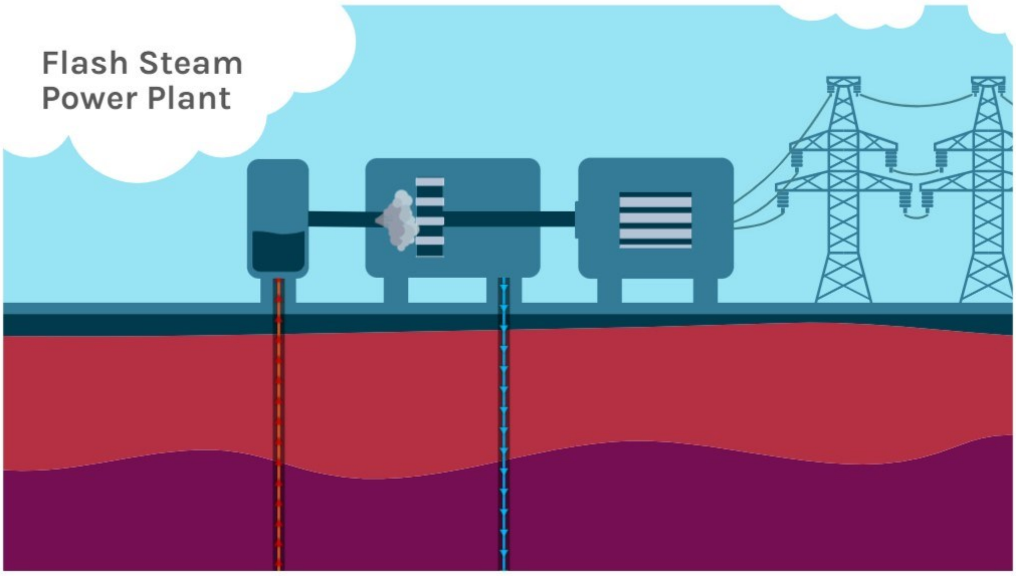

Figure 5: Flash steam power plant[15]

[14] Source: U.S. Department of Energy, https://www.energy.gov/eere/geothermal/electricity-generation (accessed: 14.02.2023)
[15] Source: U.S. Department of Energy, https://www.energy.gov/eere/geothermal/electricity-generation (accessed: 14.02.2023)

The last type of geothermal power plant is the binary cycle power plant. Binary-cycle geothermal power plants can make use of geothermal resources with temperatures below 182°C. Hence, this kind of power plant can produce electricity in locations where the other two types of power plants cannot operate. Opposite to dry steam and a flash steam power plant, the geothermal fluid never gets in contact with the turbine of a binary-cycle geothermal power plant. Instead, the geothermal fluid passes through a heat exchanger with a secondary, or binary, fluid. The binary fluid heats up and can flash into steam at lower temperatures since it has a lower boiling point than the geothermal fluid. This steam then drives the turbine, which in turn spins the electric generator, as Figure 6 depicts. Because of heating the binary fluid within the heat exchanger, the geothermal fluid cools down and is eventually reinjected.[16]

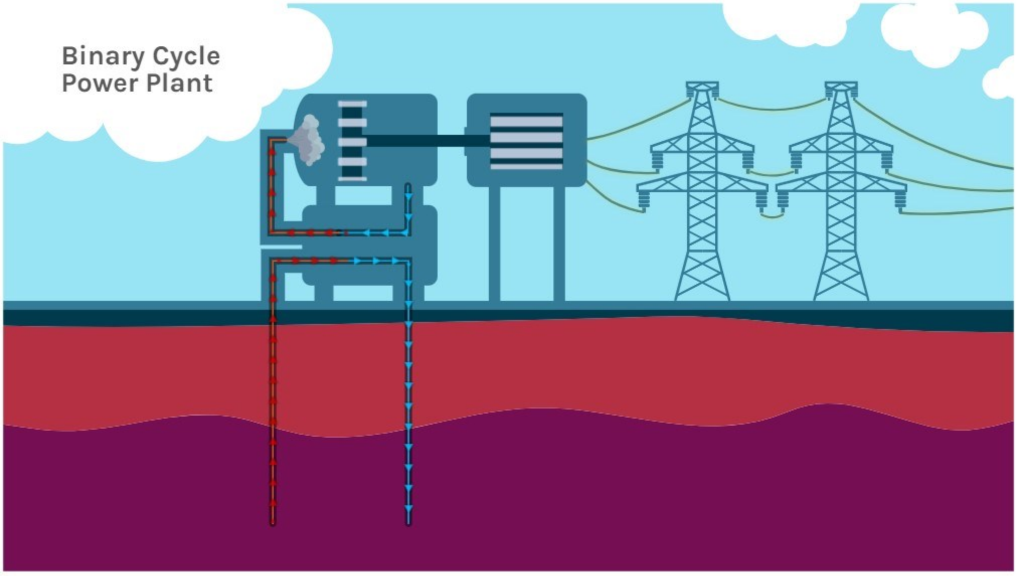

Figure 6: Binary-cycle power plant[17]

2.1.2 Geothermal systems

A geothermal system makes it possible to transport geothermal energy from the subsurface to the surface, where it can then be further used. Different types of geothermal systems exist, which differ in the depth they reach, therefore, also differ in the temperatures they are operating with. Since different applications of geothermal energy require different temperatures, the intended application determines the type of geothermal system. Figure 7 presents the required temperatures for different applications and, additionally, distinguishes between direct use and power generation.

[16] Refer to U.S. Department of Energy, https://www.energy.gov/eere/geothermal/electricity-generation (accessed: 14.02.2023)
[17] Source: U.S. Department of Energy, https://www.energy.gov/eere/geothermal/electricity-generation (accessed: 14.02.2023)

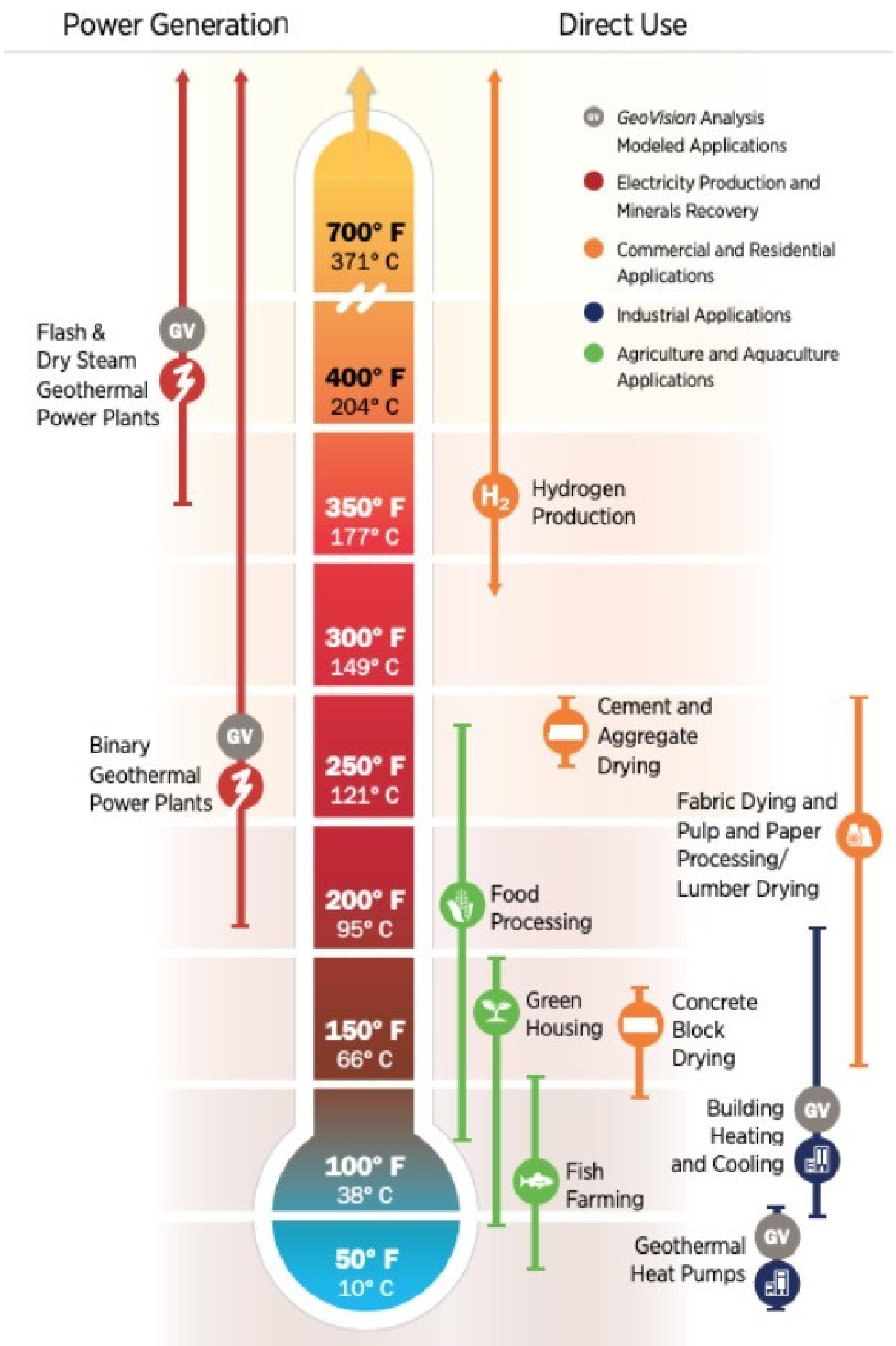

Figure 7: Applications of geothermal energy[18]

Except for the production of hydrogen, direct use applications require lower temperatures than geothermal power plants. Thus, power plants are rather located in areas with high geothermal gradients, whereas the direct use of geothermal energy is possible in almost every country. Figure 8 depicts the different types of geothermal systems, arranged by

[18] Source: Think Geo Energy, https://www.thinkgeoenergy.com/geothermal/geothermal-energy-production-utilisation/ (accessed: 14.02.2023)

their target depth and operating temperature. Namely, these systems are (from right to left) the geothermal heat collectors, the two well system, the shallow and deep geothermal probe, the hydrothermal doublet, and the hot dry rock system. Within the course of this chapter, these different types are introduced.[19]

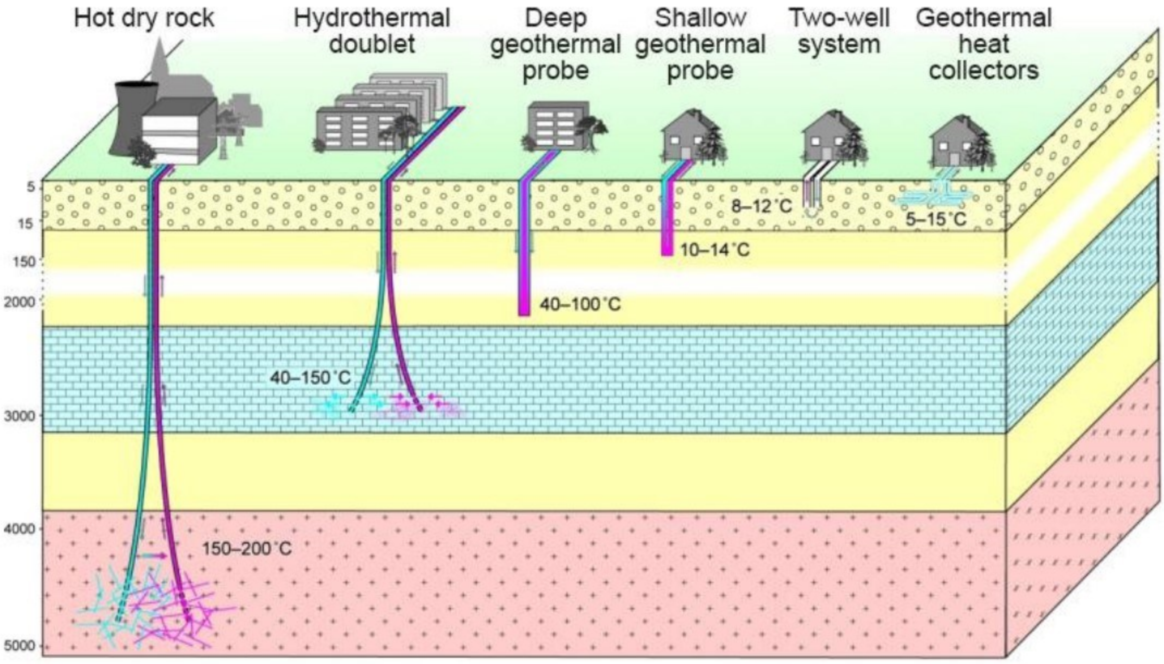

Figure 8: Geothermal systems[20]

Geothermal heat collectors and heat pump

Geothermal heat collectors make use of the relatively constant temperature of the subsurface. Independent of the season, a few meters below the surface the ground remains at a relatively constant temperature. There, the temperature is warmer than the atmosphere during the winter and cooler than the atmosphere in the summer.[21] As Figure 9 depicts, this system includes pipes made of plastic that are buried one to 1,5 meters below the frost line. Through these pipes a water-antifreeze mixture is pumped, hence circulates and exchanges heat with the subsurface. Heat collectors, like some other geothermal systems, require the implementation of a heat pump. The heat pump´s main components are the compressor, the expansion valve, the condenser, and the evaporator. Subsequently, a simplified explanation of the geothermal heat pump´s working principle is given, which can also be observed in Figure 9.

The ground piping is attached to the evaporator side of the heat pump, supplying it with fluid that has exchanged its temperature with the subsurface. A compressor then

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[19] Refer to Gegenhuber, N.; (2022)
[20] Source: Gegenhuber, N.; (2022)
[21] Refer to U.S. Department of Energy, https://www.energy.gov/energysaver/geothermal-heat-pumps (accessed: 14.02.2023)

pressurizes the fluid, which causes the fluid to heat up and vaporize. At this stage, the fluid is hot enough to transmit its heat via a distribution system inside a building. During the heating of single rooms of a building, the fluid cools down and condenses. For that reason, this side of the heat pump system is called a condenser. Before the fluid remigrates from the condenser to the evaporator, it passes through an expansion valve which further decreases its temperature so that it can absorb more heat from the ground. Generally, the expansion valve is a crucial component because it determines the direction of flow. By changing the direction of fluid circulation, the heating mode can be switched to cooling mode. In this case, the cold fluid inside the distribution system absorbs heat from the building and carries it away.[22] Of course, it is the electrically driven compressor that enables the fluid to reach a suitable temperature. However, because the heat pump is supplied with a pre-tempered fluid, the system´s electricity consumption can be reduced significantly.[23]

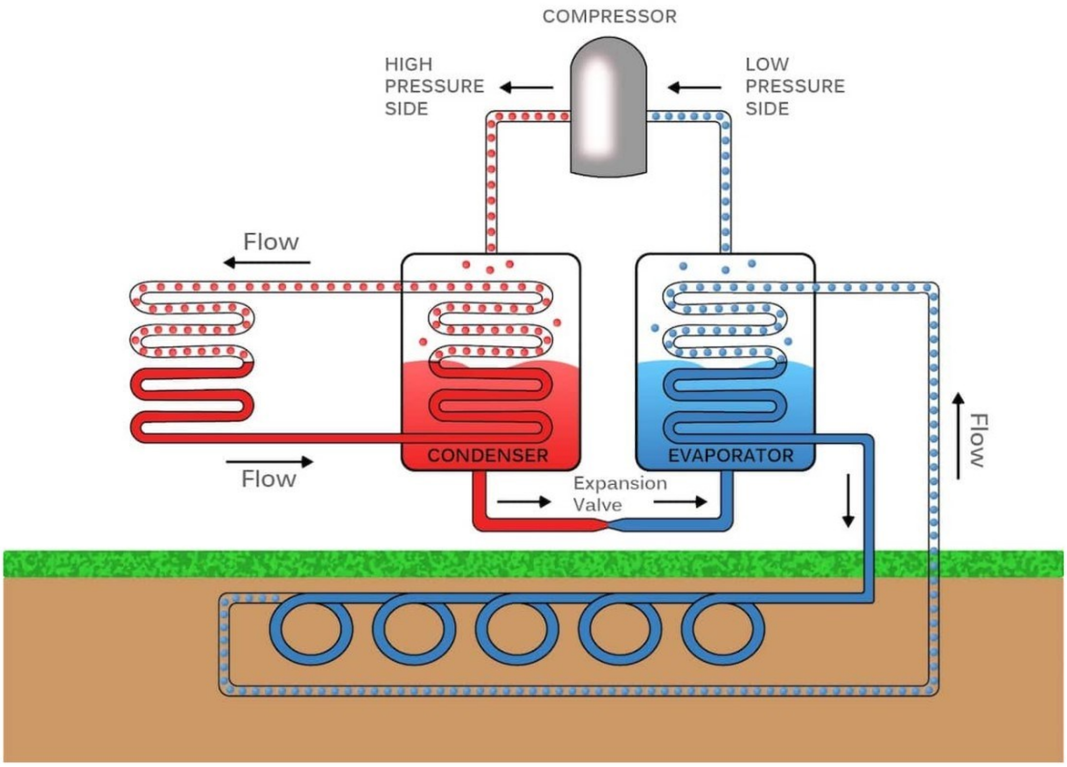

Figure 9: Geothermal heat collectors and heat pump[24]

[22] Refer to Lake Country Geothermal, https://lakecountrygeothermal.com/geothermal-heat-pumps-and-ground-loops/ (accessed: 15.02.2023)
[23] Refer to This Old House, https://www.thisoldhouse.com/heating-cooling/21014980/geothermal-heat-pump-how-it-works (accessed: 15.02.2023)
[24] Source: Green Building Advisory, https://www.greenbuildingadvisor.com/article/is-this-ground-source-heat-pump-plan-workable (accessed: 14.02.2023)

Shallow two well system

Opposite to the closed loop system of a heat collector, the geothermal system presented next, the two well system, is an open loop system. An open loop system practically means that no fluid is circulated within the system, but water is extracted from an aquifer. Depicted in Figure 10, this system consists of two wells, a production well and an injection well. The target depths of these wells can vary from just a few meters to around 40 meters, depending on the groundwater level. The temperature of the water that is pumped to the surface, in most cases, is around 10°C or slightly more. Since this temperature is not sufficient for heating purposes, this system is also equipped with a heat pump. After exchanging its heat, the cooled-down water is reinjected into the aquifer through an injection well.[25] [26]

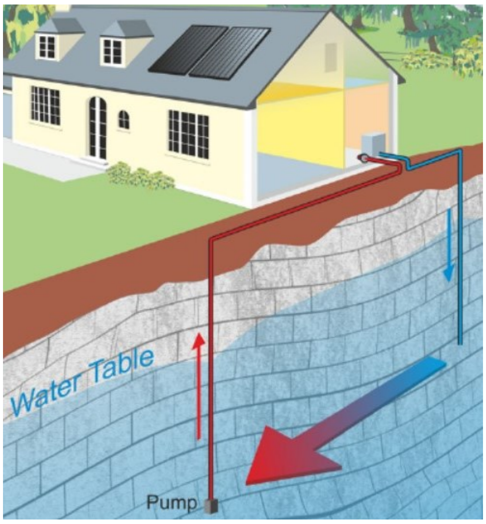

Figure 10: Shallow two well system[27]

Shallow geothermal probe

As displayed in Figure 11, the shallow and deep geothermal probes are closed systems, so no aquifer is tapped, but a fluid circulated in the underground through a u-shaped pipe. Practically, a water-antifreeze mixture heats up downhole, is pumped to the surface, and, in the case of a shallow probe, supplies a heat pump. Once cooled down the fluid re-enters the probe and another cycle of heat exchanging is initiated.

[25] In Austria, this type of geothermal system must be coordinated with the national water law, since an aquifer is tapped.
[26] Refer to Gegenhuber, N.; (2022)
[27] Source: Geological Survey Ireland, https://www.gsi.ie/en-ie/programmes-and-projects/geothermal/projects/Pages/Shallow-geothermal-energy.aspx (accessed: 15.02.2023)

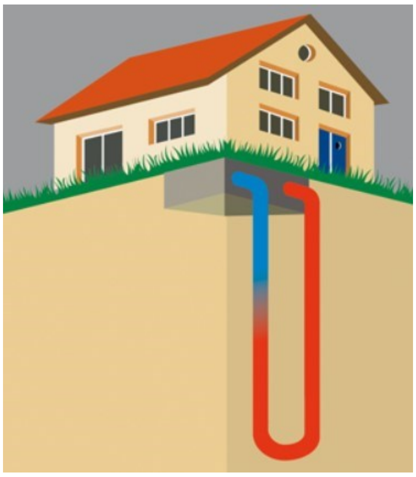

Figure 11: Geothermal probe[28]

One distinguishes shallow probes with target depths up to 400 meters, medium-deep probes with depths between 400 meters and 1.000 meters, and deep probes with depths of more than 1.000 meters. The deeper the probe, the higher the temperature the fluid can absorb. Besides differences in the depth, also the shape of probes can vary, as Figure 12 indicates by showing different cross sections.

When looking at Figure 12, the dark gray circular areas represent the borehole that is backfilled after the installation of the probe. The red circles represent the pipe through which the heated-up fluid flows upwards and the blue circle illustrates the pipe through which the fluid flows downwards. In the two types on the left side of Figure 12, the pipes run separately and parallel to each other in the borehole. These are so-called U-probes respectively double U-probes. The two types on the right side of Figure 12 are so called coaxial probes. In this case, the pipe containing the warm fluid runs in the middle of a larger pipe containing the cool fluid. The dimensions of the probes are designated in Figure 12, the borehole´s diameter, usually varies between 140 mm and 180 mm.[29]

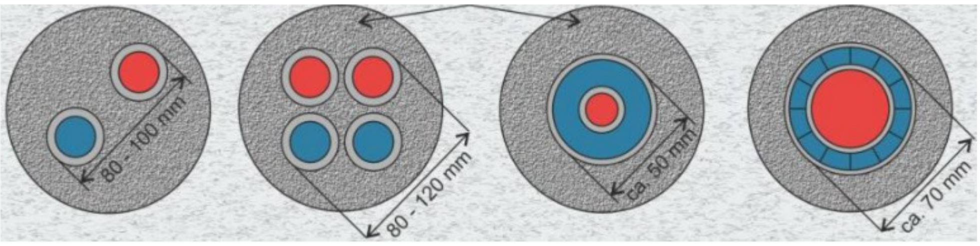

Figure 12: Different shapes of the geothermal probe[30]

[28] Source: Geologischer Dienst NRW, https://www.gd.nrw.de/ew_og.htm (accessed: 15.02.2023)
[29] Refer to Gegenhuber, N.; (2022)
[30] Source: Gregor Götzl, Geologische Bundesanstalt, https://projects-gba.geologie.ac.at/s/Rjf9LT9ABT4SsRj (accessed: 09.02.2023)

Hydrothermal doublet

The two remaining geothermal systems, the hydrothermal doublet, and the hot dry rock system are both open systems. The latter one is only used for electricity generation, whereas the hydrothermal doublet is applied for both, power generation and direct usage. The doublet is a water fountain that produces hot thermal water from a deep aquifer through a production well. Hydrothermal wells can be drilled to a depth of up to 4.000 meters and can produce water with temperatures of up to 150°C. On the surface, the thermal water does not leave the system but exchanges heat and cools down before being reinjected through an injection well. Thus, the reinjected, cooler water does not cool down the hot water in the area around the extraction well, the downhole ends of these two wells are located a few hundred meters apart from each other. The type of application depends on the temperature of the produced thermal water. Figure 13 displays a diagram of a hydrothermal doublet, however, it is also possible that numerous wells form such a system.[31]

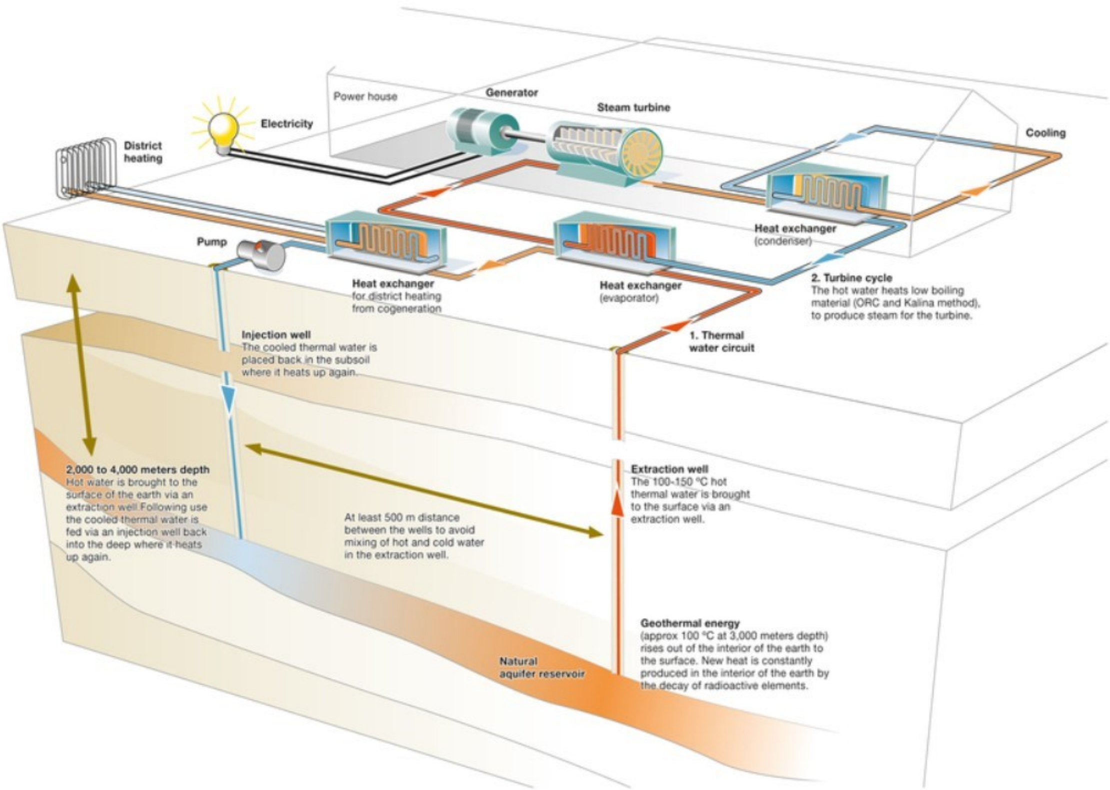

Figure 13: Hydrothermal doublet[32]

[31] Refer to Renewable energy agency, https://www.unendlich-viel-energie.de/media-library/charts-and-data/hydrothermal-geothermics (accessed: 16.02.2023)
[32] Source: Renewable energy agency, https://www.unendlich-viel-energie.de/media-library/charts-and-data/hydrothermal-geothermics (accessed: 16.02.2023)

Hot dry rock system

The hot dry rock system, also called an enhanced geothermal system, refers to the establishment of a huge heat exchanger in depths between three and six kilometers. The system includes at least two wells, an injection, and a production well that are several hundred meters apart from each other at their lowest points. Practically, water is pumped downwards through the injection well and forced into the formation with a pressure of up to 150 bar. By doing so, the formation is fractured, and its permeability increases. That way, pathways for the water between the wells are established. Due to the formation´s high temperature, the water heats up as it travels from the injection to the production well. At the surface, the water arrives through the production well with a minimum temperature of 150°C and is used for electricity generation. A risk of this method is that during the water penetration into the formation, earth tremors can occur.[33] Figure 14 presents the principle of a hot dry rock system.

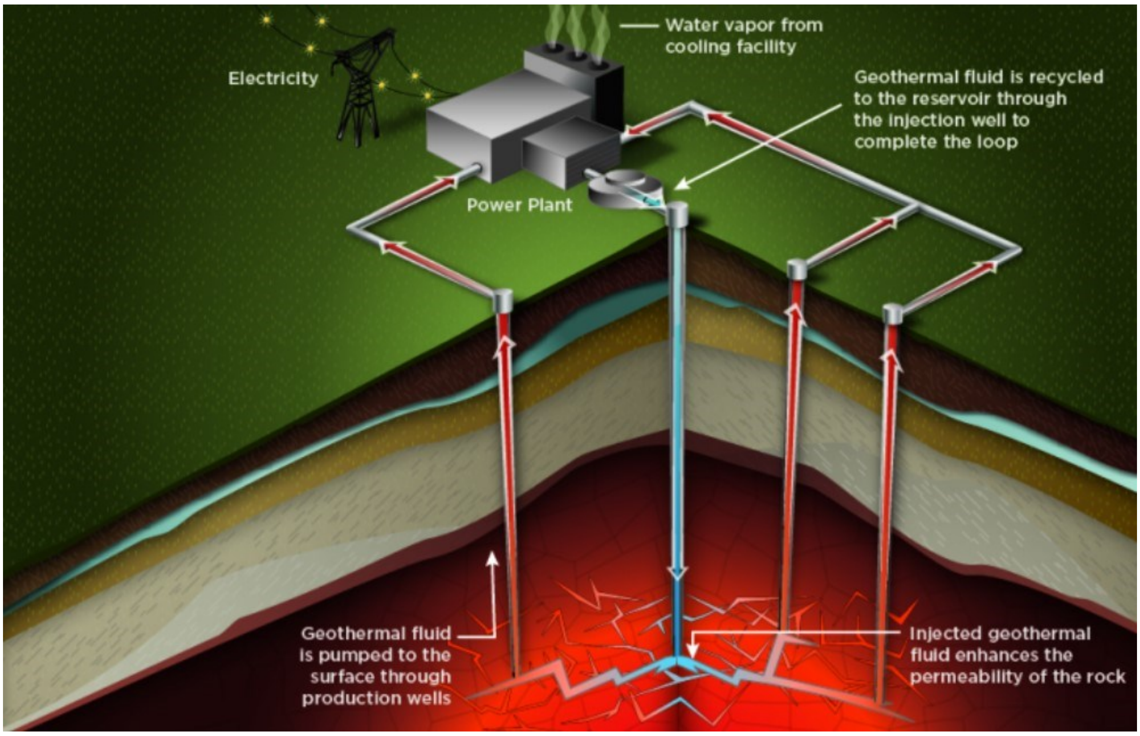

Figure 14: Hot dry rock system[34]

[33] Refer to Bundesverband Geothermie, https://www.geothermie.de/bibliothek/lexikon-der-geothermie/h/hdr-system.html (accessed: 16.02.2023)
[34] Source: Think Geo Energy, https://www.thinkgeoenergy.com/u-s-doe-announces-4-45m-funding-for-enhanced-geothermal-systems-egs-tools-technologies/ (accessed: 16.02.2023)

2.2 Status quo of geothermal energy utilization

This chapter gives an overview of the current extent of utilization of the previously described geothermal energy applications. Global figures are presented, however, the focus is on Europe and, especially, on Austria and Germany.

2.2.1 International geothermal power generation

Geothermal energy is transformed into electricity in more than 30 countries. In some countries like Indonesia, New Zealand, the Philippines, Türkiye, and the United States, geothermal power plants have been operating for decades. While other countries like Belgium, Chile, Colombia, Croatia, Honduras, and Hungary just recently began producing geothermal electricity, hence are at an early stage of development. The globally installed capacity for geothermal electricity generation was 15,96 GW at the end of 2021, distributed across five main regions, as shown in Figure 15.

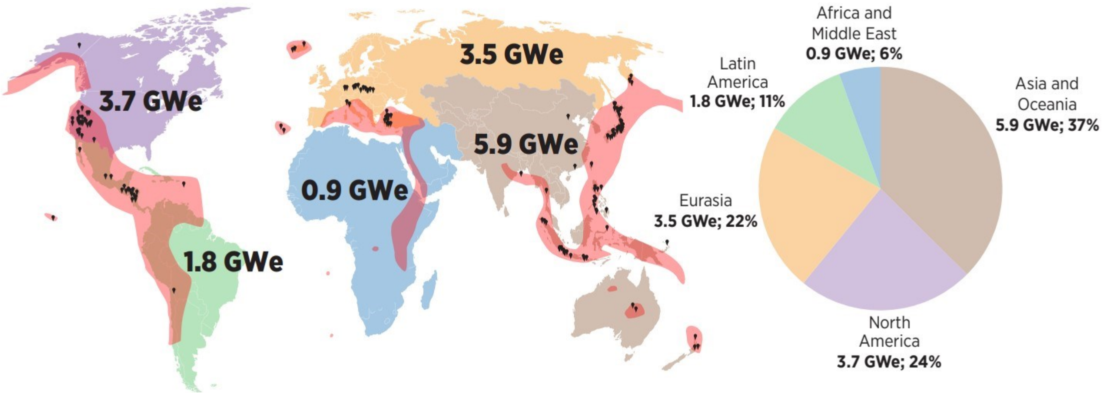

Figure 15: Installed geothermal electricity capacity in 2021[35]

However, some sources refer to a total installed capacity of less than 15 GW.[36] In this context, it is vital to mention that the installed capacity must not agree with the actual power generation, since the capacity not always is used to its full extent. Assuming that the global capacity (15,96 GW) is fully used for one year (8.760 full load hours), electricity in the magnitude of 139,81 TWh could be produced. In fact, geothermal power plants have a capacity factor of about 72%, so that on average there are 6.307 full load hours and a production of 100,66 TWh per year.[37] For comparison, Austria´s annual electricity consumption in 2019 was 73 TWh.[38]

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[35] Source: Refer to International Renewable Energy Agency and International Geothermal Association (2023), page 30

[36] Refer to International Renewable Energy Agency and International Geothermal Association (2023), page 30 p.

[37] Refer to International Renewable Energy Agency and International Geothermal Association (2017), page 6

[38] Refer to Wien Energie, https://positionen.wienenergie.at/grafiken/energieverbrauch-oesterreich/ (accessed: 01.03.2023)

The leading regions when it comes to installed capacity are Asia and Oceania with 5,9 GW, North America with 3,7 GW, and Eurasia with 3,5 GW. So, the utilization of geothermal energy for power generation is diversely advanced between regions and countries. However, these differences do not always directly correlate with the variable presence of suitable geothermal resources. Even in very favorable volcanic settings, the extent of utilization shows significant differences across regions and countries. This phenomenon can be realized in Figure 15, in which the red zones indicate high-temperature geothermal zones and the black dots indicate geothermal power plants. The two continents South America and Africa have geothermal potential, however, are not yet developed regarding geothermal power plants. [39]

To be able to classify these numbers of geothermal electricity capacity, Figure 16 presents capacities and relative shares of other electricity sources. When comparing the capacity figures, it is very clear that geothermal electricity only plays a minor role in the global electricity mix. Expressed in percentages, the geothermal share in 2021 was not even 0,5% of the renewable electricity generation and 0,13% of the total global electricity production.[40]

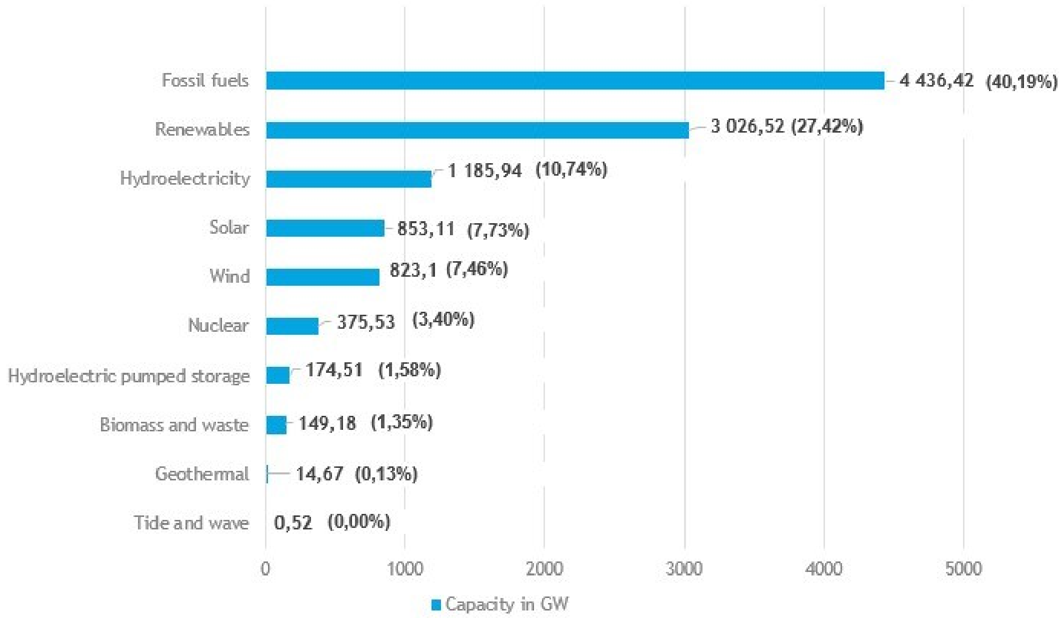

Figure 16: Installed electricity capacity worldwide in 2021[41]

European regions with very high geothermal potential are mainly present in volcanic areas in the central Mediterranean region, the eastern Mediterranean region, and the Atlantic Islands. Countries that are located in these high-potential areas are Italy, Greece, Turkey, the Azores (Portugal), and Iceland. In these regions most of Europe´s

[39] Refer to International Renewable Energy Agency and International Geothermal Association (2023), page 30 p.
[40] Refer to Statista, https://www.statista.com/statistics/267358/world-installed-power-capacity/, (accessed: 23.02.2023)
[41] Source: Statista, https://www.statista.com/statistics/267358/world-installed-power-capacity/, (accessed: 23.02.2023) (slightly modified)

geothermal power generation takes place. Nevertheless, raised geothermal gradients, hence geothermal potentials, are also present in European sedimentary basins. One example is the Pannonian Basin which stretches across Bosnia and Herzegovina, Croatia, Hungary, Austria, Poland, Romania, Serbia, Slovenia, Slovakia, and Ukraine. Other examples are the Upper Rhine-Graben in France and southern Germany, and the Southern Permian Basin located in Poland, northern Germany, the Netherlands, the North Sea, and England. In these regions, geothermal power generation is practicable and in a few of these, power plants exist.

Installed geothermal capacity for electricity production in Europe is about 3,54 GW, which accounts for around 22% of the global quantity. Figure 17 displays the distribution of installed geothermal electricity capacity across European countries. It is to mention, that the Russian geothermal power plants are located in the eastern part, far away from Europe, and also most of Turkey´s capacity is in its Asian part, east of the Bosporus.

As can be seen in Figure 17, Turkey has the most capacity installed, expanding it recently from 91 MW in 2010 to 1.688 MW in 2020. Italy possesses an installed capacity of 944 MW, while Iceland´s capacity amounts to 754 MW. Apart from these three countries, minor capacities are located on the Azores with 33 MW, in Belgium with 4,5 MW, and in France with 1,7 MW.[42] Geothermal power generation in Austria and Germany is covered separately in Chapter 2.2.3 and Chapter 2.2.4.

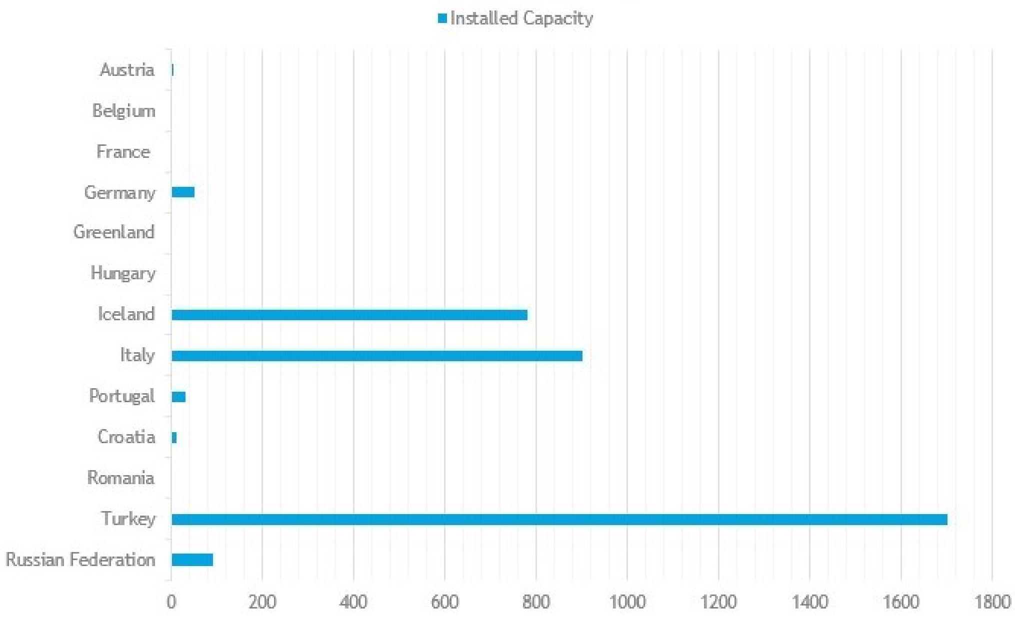

Figure 17: Installed geothermal electricity capacity in Europe[43]

[42] Refer to International Renewable Energy Agency and International Geothermal Association (2023), page 100 pp.

[43] Source: International Renewable Energy Agency and International Geothermal Association (2023), page 101(slightly modified)

2.2.2 International direct utilization of geothermal energy

The worldwide direct use of geothermal energy is of higher significance compared to geothermal electricity production. Within the last decades, direct utilization experienced considerable growth in the application, which can be proved in the figures. In 2020, direct utilization of geothermal energy was performed in 88 countries. This is an increase from 28 countries in 1995, 58 in 2000, 72 in 2005, 78 in 2010 and 82 countries in 2015. From 2015 to 2020, the direct use industry experienced a 52% growth in installed capacity and a 74% growth in utilization. This growth can mainly be explained by the sharp increase in the number of heat pump installations.

In 2020, the global installed capacity for direct utilization was 107,4 GW, which is more than seven times the capacity for geothermal electricity production. Annually, geothermal energy is directly used in the magnitude of 1.021 PJ which is equivalent to around 284 TWh.[44] For comparison, in 2019, Austria required 158 TWh of energy for heating purposes.[45] How this installed capacity is distributed over the globe, is shown in Figure 18. It can be seen that the Asia and Oceania region is the global leader, followed by Eurasia and North America.

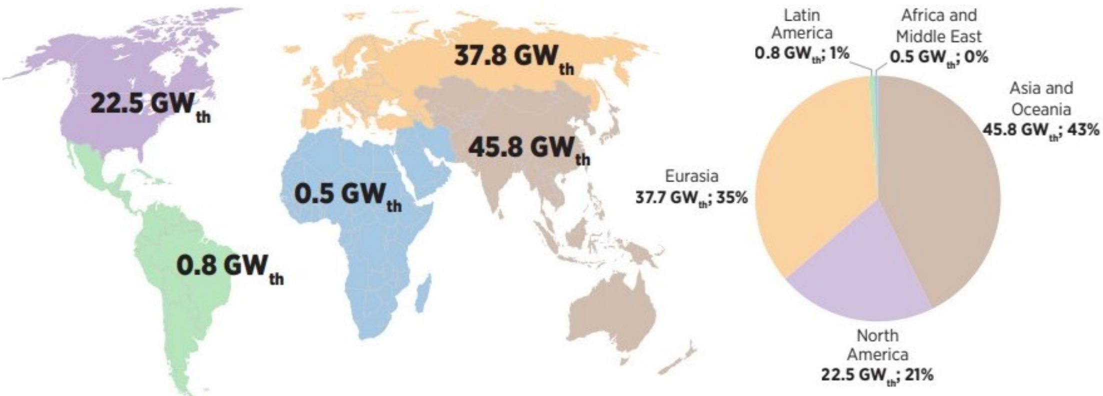

Figure 18: Global installed direct utilization capacity in 2020[46]

When it comes to direct use, it is of interest to know for what purpose geothermal energy is directly used. Figure 19 presents the different purposes and the rapid development of their shares from 1995 to 2020.

[44] Refer to Lund, J.W.; Toth, A.N.; (2020), page 1 p.
[45] Refer to Wien Energie, https://positionen.wienenergie.at/grafiken/energieverbrauch-oesterreich/ (accessed: 01.03.2023)
[46] Source: International Renewable Energy Agency and International Geothermal Association (2023), page 48

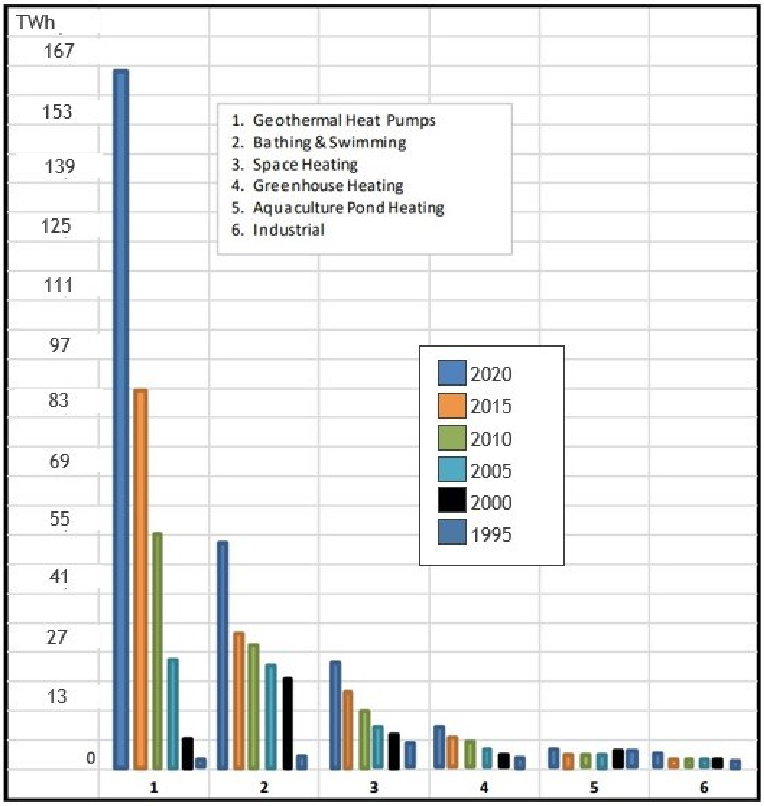

Figure 19: Purposes of direct utilization[47]

As can be seen in Figure 19, geothermal heat pumps represent the most important application, accounting for around 72% of direct utilization in 2020. This tendency can also be observed in the two countries with the highest installed capacity, China and the United States of America, where 65% respectively 98% of direct utilization constitute to geothermal heat pump applications. Figure 20 shows the countries with the largest capacities and, additionally, presents their shares of geothermal heat pump application.[48]

[47] Source: Lund, J.W.; Toth, A.N.; (2020), page 4 (slightly modified)
[48] Refer to Lund, J.W.; Toth, A.N.; (2020), page 1 p.

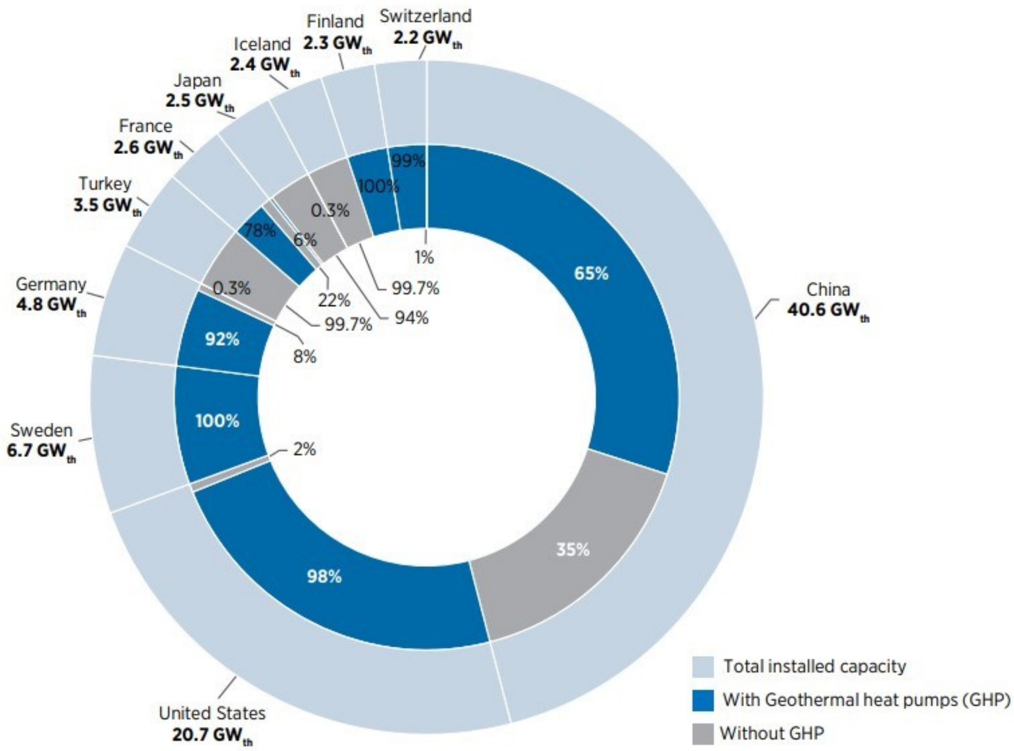

Figure 20: Installed direct utilization capacities by countries[49]

In Europe, many countries have more than 100 MW of installed geothermal heating capacity and some countries even have capacities of more than 1.000 MW. In terms of installed capacity, Germany and Sweden are the leading countries in Europe. This can be observed in Figure 21, which shows the capacities of European and adjacent countries.

[49] Source: International Renewable Energy Agency and International Geothermal Association (2023), page 49

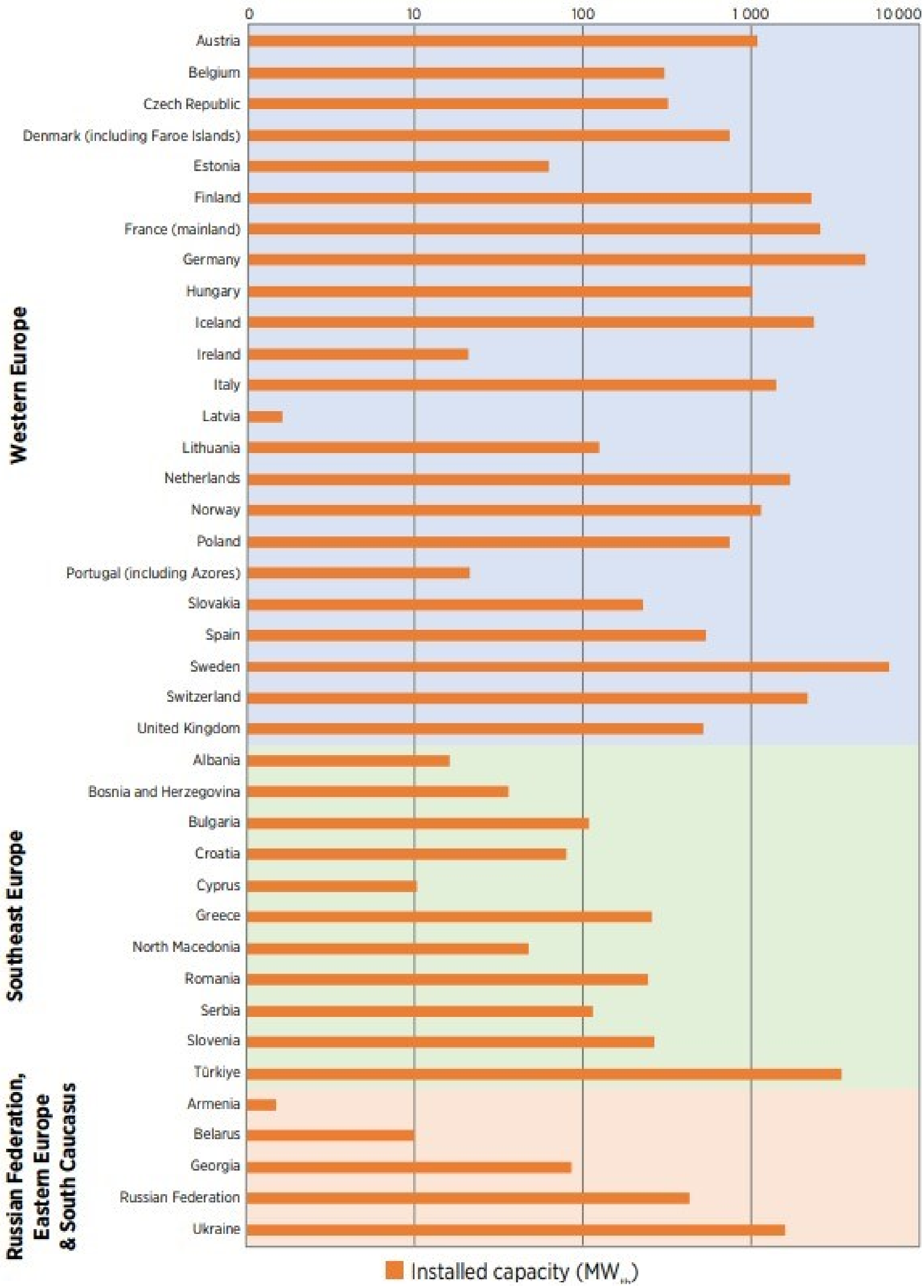

Figure 21: Installed capacity for direct use in Europe[50]

When comparing the installed geothermal capacity for direct use relative to the country´s inhabitants, the global top five countries are all located in Europe. Namely, these are Sweden with a total capacity of 6.680 MW, Iceland with 2.373 MW, Finland with

[50] Source: International Renewable Energy Agency and International Geothermal Association (2023), page 103

2.300 MW, Switzerland with 2.197 MW, and Norway with 1.150 MW. Especially, Iceland is a world leader in geothermal direct use, as over 90% of its buildings are heated by geothermal energy. The application of geothermal heat pumps is significant in Europe compared to the other continents. Sweden, Germany, and Finland are in the global top five countries regarding installed geothermal capacity used for heat pumps, following China and the United States. Figure 22 shows what other direct use applications are common in Europe.[51]

Figure 22: Direct use applications in Europe[52]

2.2.3 Geothermal energy utilization in Austria

Austria´s resources of hot thermal waters are situated in the country´s eastern part, concretely in the Molasse Basin, the Styrian Basin, and the Vienna and Pannonian Basin. However, only in the Molasse Basin in Upper Austria and in the Styrian Basin, geothermal plants have been established to produce geothermal energy. In the Pannonian Basin, east of Vienna, a development project called "GeoTief Wien" is currently being executed. Its goal is to install hydrothermal power plants in the near future. As Figure 23 presents, seven hydrothermal plants, that are plants that produce geothermal energy for heating purposes, are located in Upper Austria and three such plants exist in the Styrian Basin.

[51] Refer to International Renewable Energy Agency and International Geothermal Association (2023), page 102 pp.
[52] Source: International Renewable Energy Agency and International Geothermal Association (2023), page 105

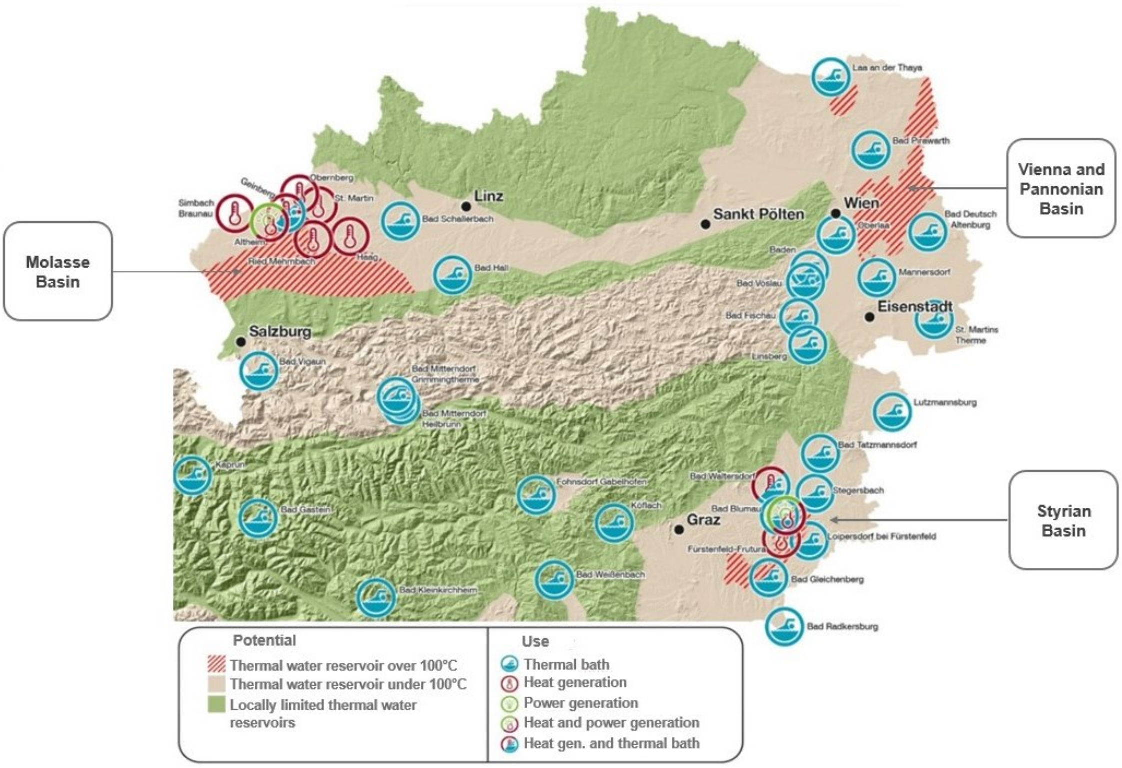

Figure 23: Geothermal plants in Austria[53]

The power plants in Bad Blumau (Styria) and Altheim (Upper Austria) not only produce thermal water for direct use but also generate electricity.[54] Both plants are hydrothermal doublets, hence, consist of a production and an injection well. With a flow rate of 25 liters per second, the plant in Bad Blumau produces hot water with a temperature of 107° Celsius. Its production well and its injection well have both measured depths of around 3.000m. The Bad Blumau plant has a capacity for electricity generation of 0,18 MW, while its capacity for heating is 7,6 MW. The produced electricity is of such quantity that a local hotel and thermal bath can be supplied with it.[55] The plant in Altheim consists of a production well with a measured depth of 2.305 meters, while the injection well is inclined and has a measured depth of 3.078 meters. Through the production well, geothermal water with 104°C is produced with a flow rate of 70 liters per second. Its thermal capacity amounts to 14,4 MW, which enables the plant to supply more than 700 households with heat. Its electricity generation capacity is 1 MW.[56] Austria´s biggest geothermal plant is situated in the small village of Mehrnbach, next to Ried im Innkreis. It is a triplet, consisting of two production wells and one injection well with measured

[53] Source: Geothermie- Österreich, https://www.geothermie-oesterreich.at/was-ist-geothermie/tiefe-geothermie/tiefe-geothermie-in-%C3%B6sterreich/, (accessed: 06.03.2023), (slightly modified)
[54] Refer to Goldbrunner, J.; Götzl, G.; (2019): Geothermal Energy Use, Country Update for Austria, page 2-5
[55] Refer to Tiefe Geothermie, Bad Blumau, https://www.tiefegeothermie.de/projekte/bad-blumau-steiermark (accessed 06.03.2023)
[56] Refer to Tiefe Geothermie, Altheim, https://www.tiefegeothermie.de/projekte/altheim-oberoesterreich (accessed: 06.03.2023)

depths of 2.730 meters, 2.592 meters, and 1.910 meters. Thermal water is produced with a temperature between 92°C and 110°C and a flow rate of 100 liters per second.[57] Its thermal capacity amounts to 19 MW. With this capacity, the plant can supply heat to 2.258 apartments, 169 houses, and 97 commercial facilities.[58]

To summarize the geothermal energy usage in Austria, the following figures can be presented:

By late 2020 a total of 77 deep geothermal wells, so wells with a depth of at least a few hundred meters, had been drilled in Austria. When accumulating their lengths, a total of 135 kilometers have been drilled for geothermal purposes.[59] The total installed capacity of deep geothermal systems amounted to 105 MW at the end of 2020 and this figure is still valid. Geothermal power plants in Austria contribute less than 0,1% to the country´s total electric power generation.[60] In 2020, 421,39 GWh (17,88% of total geothermal energy production) was used for district heating, 139,17 GWh (5,80%) for greenhouse heating, and 87,78 GWh (3,66%) for bathing and swimming. Compared to deep geothermal energy usage, shallow geothermal energy usage is much more developed in Austria. The installed capacity of geothermal heat pumps is estimated to be 10 times higher than the one of deep systems. This can be underlined by the energy production of geothermal heat pumps, which amounted to 1752,50 GWh (72,99%) in 2020. In total, deep and shallow geothermal systems produced 2.401,11 GWh of thermal energy (power generation excluded) in 2020. To put this figure in context, it can be stated that around 1,6% of Austria´s total energy used for heating purposes comes from geothermal sources.[61]

2.2.4 Geothermal energy utilization in Germany

Geothermal resources, especially hot thermal water, are unevenly distributed across Germany. Figure 24 shows in which German areas geothermal potentials exist and what maximum temperatures the underground water can reach. The areas with the most potential are the Molasse Basin in southern Germany, the North German Basin, and the Upper Rhine Graben.

[57] Refer to Tiefe Geothermie, Ried im Innkreis, https://www.tiefegeothermie.de/projekte/ried-im-innkreis (accessed 06.03.2023)
[58] Refer to Lund, J.W.; Toth, A.N.; (2020), page 17
[59] Refer to Goldbrunner, J.; (2020): Geothermal energy utilisation in Austria, page 541
[60] Refer to Goldbrunner, J.; Götzl, G.; (2019): Geothermal Energy Use, Country Update for Austria, page 7
[61] Refer to Goldbrunner, J.; Götzl, G.; (2019): Geothermal Energy Use, Country Update for Austria, page 6

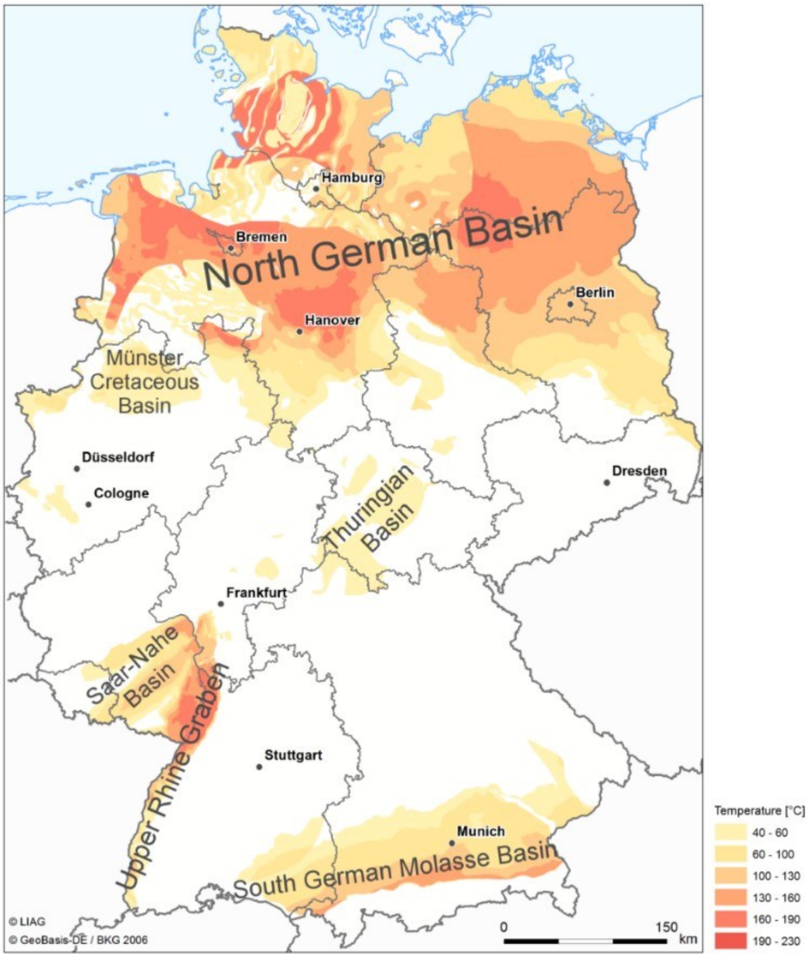

Figure 24: Geothermal resources in Germany[62]

At the moment, 42 geothermal power plants are operating in Germany. The majority of these plants, concretely 30, exclusively extract hot water for heat production. 10 plants combine the production of heat with power generation, while only two plants solely generate electricity. Currently, 12 power plants are under construction, one of them with the later purpose of generating electricity, and 82 more geothermal plants are currently in the planning phase (February 2023). Additionally, seven geothermal research wells and around 170 wells for producing thermal water for balneology purposes exist in Germany. Accumulated, Germany´s geothermal plants have a thermal capacity of 417 MW and an electricity capacity of 46 MW. The average drilling depth to develop deep geothermal resources is around 2.500 meters.

Nine of the 12 electricity-producing power plants are located in the Molasse Basin, in the State of Bavaria and the remaining three plants are located in the Upper Rhine Graben, in the States of Rhineland-Palatinate and Baden-Württemberg. Not only the majority but also the ones with the highest capacities are located in Bavaria. Namely, these are the plants in Dürnhaar, Kirchstockach, and Traunreut, each with a capacity of 5,5 MW.

[62] Source: Kimberley Foundation, https://kimberley-foundation.org/2019/04/geothermal-in-germany/ (accessed: 07.03.2023)

Dürnhaar produces thermal water with a temperature of 141°C from a depth of 3.926 meters. Its flow rate is 133 liters per second. The plant in Kirchstockach delivers similar production values, while the one in Traunreut produces 168,6 liters per second of 120°C hot water from a depth of 4.646 meters.[63] Together, the plants in Dürnhaar and Kirchstockach supply 32.000 households with electricity.[64]

When it comes to the plants with heat production capacities, also the majority of plants is situated in the south of Germany, in the areas of the Upper Rhine Graben and particularly in Munich and its vicinity. The remaining plants are distributed as follows. Four plants exist in the state of North Rhine-Westphalia, five plants in the east part of the North German Basin, and one plant in Zwickau, Saxony. However, it needs to be stated that these plants´ capacities are only a fractional amount of the capacities of the plants in Germany´s south. Especially, some plants in Munich and its vicinity have thermal capacities above 20 MW. With 50 MW of capacity, the plant in Sendling, Munich is the largest one. It produces at a rate of 115 liters per second from a depth of 2.809 meters. At the surface, the thermal water arrives at 107°C.[65] This plant can produce as much heat, as 80.000 people need in their heat requirement.[66] Since Munich and its vicinity possess almost 20 geothermal power plants, it can supply whole urban districts with geothermal heat and electricity.

Compared to deep geothermal usage, shallow geothermal usage, hence the application of geothermal heat pumps, is much more developed in Germany. More than 470.000 heat pumps are currently installed in Germany. Accumulated, these pumps have a capacity of 4.700 MW, which is 10 times the value of the deep geothermal capacity.[67] These 470.000 geothermal heat pumps cover around 2% of the country´s residential heat demand.[68]

[63] Refer to Bundesverband Geothermie, https://www.geothermie.de/geothermie/geothermie-in-zahlen.html (accessed: 07.03.2023)
[64] Refer to Stadtwerke München, https://www.swm.de/energiewende/oekostrom-erzeugung (accessed: 07.03.2023)
[65] Refer to Bundesverband Geothermie, https://www.geothermie.de/geothermie/geothermie-in-zahlen.html (accessed: 07.03.2023)
[66] Refer to Stadtwerke München, https://www.swm.de/energiewende/oekostrom-erzeugung (accessed: 07.03.2023)
[67] Refer to Bundesverband Geothermie, https://www.geothermie.de/geothermie/geothermie-in-zahlen.html (accessed: 07.03.2023)
[68] Refer to Lund, J.W.; Toth, A.N.; (2020), page 19

2.3 Potential and outlook of geothermal energy usage

To be able to assess the future role of geothermal energy, it is necessary to take a quick holistic look at the development of energy supply. The rising figure of population and economic and industrial growth are increasing the global energy demand, hence, intensifying the problem of climate change. To be able to slow down climate change and move towards a sustainable and environmentally sound economy, global efforts are undertaken to transition towards renewable energy sources. This is a complex process in which fossil fuels must be phased out continuously and replaced with renewable and sustainable energy sources. In addition, other measures, such as energy efficiency or behavioral changes, are required as well. Since fossil fuel power plants are large emitters of greenhouse gases, they are increasingly decommissioned for environmental reasons. In 2020 and 2021, an average of 62 GW of fossil fuel-based electricity capacity were decommissioned annually. Considerable renewable capacity for electricity generation will be required to replace these plants. So far, variable hydropower, solar and wind solutions are not capable of fully replacing these plants. Hence, geothermal energy, with its constant and high plant capacity factor, is a crucial element that can contribute to the stabilization of electricity grids. Additional advantages as an electricity source, are its low greenhouse gas emissions, its small ecological footprint, and its long life cycle when adequately managed.

Generally, geothermal energy holds a unique place in the renewable energy ecosystem because unlike other renewable energy sources, it can provide both electricity and heat, as well as value-added mineral extraction. Heating and cooling accounts for almost half of the world´s total energy usage, whereat the majority of it derived from burning fossil fuels. This is why heating and cooling applications produce approximately 40% of greenhouse gas emissions in the energy sector. Because of the disadvantageous climate effects of using fossil fuels, it is expected that bioenergy, solar thermal and geothermal energy will gradually expand their shares in providing heat for industrial processes, cooking, space heating and cooling, and domestic hot water supply. The transportation of heat over long distances without loss of temperature is economically challenging. Thus, the transformation of the heating sector from fossil fuels to renewable sources highly depends on local characteristics affecting heat generation, distribution, utilization, and storage. In the building sector, the utilization of geothermal heat in local district heating systems is becoming increasingly common, especially across Europe and parts of China. Summarized, as a source of heat, geothermal energy is scalable, has low operating costs, offers increased efficiency since supplying heat directly, and minimizes electricity consumption for heating and cooling. Again, it can present a long-lasting source of sustainable heat.

However, recent global events, such as the COVID-19 pandemic and the uncertainty of energy supply due to war, have affected global energy markets. It can be stated that, due to the quest for energy security and independence, a growing interest in accelerating the development of geothermal resources is taking place. Geothermal energy can play a more significant role in meeting global energy needs, for both electricity and direct use.

This is because geothermal resources are widely available and on top, it is a cost-effective and weather-independent source of renewable energy.

However, there is also a downside to geothermal energy technology. Therefore, its extraction, in many cases, is underdeveloped, even in regions that have great geothermal potential. In comparison with other energy productions, geothermal projects take longer to fully develop, require higher capital expenditures in advance, and present a high risk during the early phases of exploration. Additional challenges are posed by financing, policy and regulatory frameworks, institutional and technical know-how, and technological progress. Certainly, national policies and regulations are key to successfully developing geothermal projects, and these strongly vary among countries. As a result, the geothermal industry has developed in different ways around the world. To be able to overcome these diverse barriers, the International Renewable Energy Agency (IRENA) lists possible measures to achieve progress in the utilization of geothermal energy:

- Expansion and interconnection of regional electricity grids to export geothermal electricity from countries with high potential. The eastern Caribbean Island can be mentioned as example. If these countries are connected with undersea cables, it would allow countries with geothermal resources to export geothermal electricity to neighboring islands without adequate resources.
- Usage of technology expertise from the oil and gas industry to scale up geothermal development.
- Recovery of minerals from produced geothermal waters.
- Intensifying the usage of geothermal energy for green hydrogen production.
- Improvement of the efficiency of electricity production from medium temperature geothermal resources.
- Accelerating and expanding research and development in enhanced geothermal systems (hot dry rock).
- Promotion of application of geothermal resources for heating and cooling through geothermal heat pumps.
- Application of advanced district heating technology and expanding the use of geothermal heat in agriculture, food processing, and industry.[69]

2.3.1 Outlook for geothermal energy in Austria

The potential and the current installed geothermal capacities of Austria have been covered in Chapter 2.2.3. This chapter deals with the possible future of geothermal energy in Austria.

One third of the Austrian energy consumption and around 20% of Austria´s CO_2 emissions are caused by space heating and warm water supply. To achieve Austria´s goal of being climate-neutral by 2040, the transition towards renewable energy sources such as geothermal energy in the heating sector must be accelerated urgently. Thus, the

[69] Refer to International Renewable Energy Agency and International Geothermal Association (2023), page 8 pp.

development of geothermal energy resources is supposed to become a crucial part of the future Austrian energy system.[70]

Development goals

Despite already using it for a long time, Austria uses its geothermal energy resources only on a relatively small scale. Geothermal energy production is happening mostly in the countryside, away from the highly populated areas. This is mainly because of a complex and partly outdated legislative framework concerning the exploration and extraction of hydrothermal resources. To develop and expand the utilization of deep geothermal energy for direct use and electricity generation, it is essential to revise this legislative framework.[71] The current law for utilization of geothermal energy is discussed in Chapter 2.5.1. Apart from judicial barriers, further obstacles of various natures thwarted a more extensive application of geothermal energy in Austria. To fight these hurdles and speed up progress, Austria´s Ministry of Climate Protection, Environment, Energy, Mobility, Innovation, and Technology worked out a roadmap for the future application of geothermal energy. In total, more than 20 research and innovation goals have been worked out. The following are of interest in the context of this thesis:

- Efficient and environmentally friendly drilling in urban areas for shallow geothermal applications: The challenge is to drill efficiently to depths of more than 100 meters under complicating circumstances like constricted areas. Since taking place in urban areas, these operations should produce as little sound and emissions as possible.
- Promotion of shallow geothermal applications at existing buildings: The installation of geothermal applications at existing buildings, especially in urban areas, is essential and closely linked with reconstruction jobs.
- Improvement of the probability of success and reduction of development time for deep geothermal projects: The development phase of geothermal projects varies according to the dimension of the project between three and seven years. Additionally, these projects require high investment costs before their success can even be confirmed. To keep up with other renewable energy sources, geothermal energy development phases need to be reduced by 30-50% and hedge models for investments must be supplied. This should mainly be fulfilled by improved and standardized geological prospecting and projection and unburdened access to geological and geophysical data.
- Further development of drilling technologies and borehole completion to achieve less drilling costs: Because of high return rates in the oil and gas industry, the deep drilling technology in the last decades has not been under pressure concerning economic optimization. Due to the phase out of fossil energy exploration in Europe, innovative concepts are required to enable efficient, environmentally friendly, and low emission drilling.
- Improved integration of deep geothermal energy into energy systems: To force the expansion of deep geothermal energy, its portfolio of applications must be enlarged.

[70] Refer to Energy Innovation Austria (2021), page 2
[71] Refer to Geothermie Österreich, https://www.geothermie-oesterreich.at/was-ist-geothermie/tiefe-geothermie/tiefe-geothermie-in-%C3%B6sterreich/ (accessed: 14.03.2023)

Especially its integration into larger heating networks of urban areas and its application in industrial and agricultural processes must be managed.

- Usage of existing oil and gas infrastructure like wells for geothermal purposes: More than 1.000 active oil and gas wells exist in Austria, of which many can be used for geothermal purposes in the future. Potentially, these wells can be converted into deep heat exchangers. Indeed, to be able to realize these conversions, the legal framework needs to be adjusted and innovative technological concepts are required.
- Preparation of pilot facilities for hot dry rock systems: Hot dry rock technology is independent of the presence of thermal water. Therefore, it could be applied in many parts of Austria. Unfortunately, this type of geothermal system still waits for its technological breakthrough, even though pilot projects globally exist for around 50 years. One reason is the insufficient effort in research- and development (R&D) as well as the frequent occurrence of minor earthquakes linked with hot dry rock activities. However, recently many countries intensified their effort in R&D and so does Austria. Austria plans to gather data concerning geothermal resources, possible risks, installation costs, and options for integration into the energy system until the year 2030. Subsequently, the first pilot projects are planned to be installed, to prepare the comprehensive application of hot dry rock technology in Austria.
- Extraction of resources from geothermal fluids.
- Usage of existing mining infrastructure for storage reasons: Existing hollow spaces in the subsurface like tunnels, mining shafts, and bunkers are supposed to be examined if they are qualified as storage caverns. Water could be pumped into these reservoirs, where it warms up and is finally pumped back to the surface at a higher temperature.[72]

Goals in figures

The innovation and research goals are meant to use Austria´s geothermal potential at the best possible rates. Parallel to these goals, also concrete target figures concerning the future geothermal energy production per annum have been formulated in the roadmap. Thereby, the four different geothermal systems of deep hydrothermal technology, hot dry rock technology, deep heat exchanger technology, and shallow geothermal technology (maximum depth of 300 meters and maximum temperature of 30°C) have been considered separately.

- Hydrothermal technology: In 2018, hydrothermal applications in Austria produced 0,003 TWh of electricity and 0,289 TWh of heat. In 2030, the electricity production should increase to 0,04 TWh and the yearly generation of heat should accumulate to 2 TWh. In 2050, the target electricity generation respectively heat production are 0,6 TWh and 8 TWh. Currently, 9,2 TWh of hydrothermal resources are known in Austria. This means, that in 2050, almost the full potential is supposed to be utilized.

[72] Refer to Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (2022), page 30 pp.

- Hot dry rock technology: Today, and also in the next few years this technology is not expected to contribute to Austria´s energy production. In 2050, it is aimed that hot dry rock applications annually generate 0,1 TWh of electricity and 1,2 TWh of heat.
- Deep heat exchanger technology (deep probes): Currently, this technology is not utilized in Austria, even though resources of 1,2 TWh are known. The intended yearly heat production figures by the years 2030 and 2050 are 0,4 TWh and 1 TWh.
- Shallow geothermal technology: In 2018, shallow geothermal applications produced 1,8 to 2,2 TWh of heating and cooling energy. In 2030 the target production amounts to 6,2 TWh, while in 2050, 15 TWh of heating and cooling energy should be generated by this technology. Theoretically, shallow geothermal applications could cover more than 50% of Austria´s low temperature demand (below 30°C).[73]

To put these figures into context, as presented before, the total Austrian energy consumption for heating in 2019 was 158 TWh, of which 34% was derived from renewable energy sources.[74]

Accomplishing the projected target figures for 2030 means that 25% of the Austrian geothermal resources are developed, 500.000 accommodation units can be supplied by geothermal district heating, and emissions can be reduced by 600.000 tons of CO_2 due to the substitution of fossil fuels.[75] This means Austria´s total CO_2 emission can be reduced by 0,77%.[76] Achieving the 2050 target figures for geothermal district heating means that the district heating share of renewable energy sources can be increased from today´s 46% to 86%.[77]

As already mentioned in Chapter 2.2.3, a project called “GeoTief Wien” is currently being undertaken in the Pannonian Basin, east of Vienna. When discussing geothermal energy´s future in Austria, this is the biggest and most concrete project. Between 2016 and 2022, the geological subsurface of Vienna and its vicinity was extensively investigated, including the drilling of exploration wells and seismic logging. The results are promising, confirming a hot hydrothermal reservoir in 3.000 meters depth. Taking the city of Munich as a role model, hydrothermal plants are planned to develop this reservoir. When successfully installing these plants, it is possible to supply district heating to around 125.000 accommodation units in Vienna. As a pilot project, the first hydrothermal plant is supposed to be installed in Aspern, a quarter in the east of Vienna. This plant will produce thermal water of 100°C and will have a capacity of 20 MW, with which

[73] Refer to Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (2022), page 23
[74] Refer to Wien Energie, https://positionen.wienenergie.at/grafiken/energieverbrauch-oesterreich/ (accessed 01.03.2023)
[75] Refer to Geothermie Österreich, https://www.geothermie-oesterreich.at/was-ist-geothermie/tiefe-geothermie/tiefe-geothermie-in-%C3%B6sterreich/ (accessed: 14.03.2023)
[76] Refer to Umweltbundesamt, https://www.umweltbundesamt.at/klima/treibhausgase (accessed: 24.08.2023)
[77] Refer to Geothermie Österreich, https://www.geothermie-oesterreich.at/was-ist-geothermie/tiefe-geothermie/tiefe-geothermie-in-%C3%B6sterreich/ (accessed: 14.03.2023)

20.000 households can be supplied with heat. The commissioning of the hydrothermal power plant in Aspern is aimed to be in 2026.[78]

2.3.2 Outlook for geothermal energy in Germany

The potential and the current installed geothermal capacities of Germany have been covered in Chapter 2.2.4, this chapter deals with the possible future of geothermal energy in Germany.

Development goals

In Germany, the heating sector annually requires 1.400 TWh of energy, which are 56% of the total national energy demand. However, only 15% of the heating energy comes from renewable sources. Thus, especially in this sector, a transformation process is necessary to achieve decarbonization and climate neutrality in 2045. Geothermal energy is expected to become an integral part of Germany´s transformed heating sector. However, to realize an area-wide integration of geothermal energy applications into Germany´s energy mix requires effort of politics, economy, science, administration, and citizens. Therefore, prestigious German research institutes published roadmaps for shallow and deep geothermal energy use in Germany. In these roadmaps, recommendations are given and goals for geothermal development are formulated. For the development of deep geothermal applications, the recommended actions are the following:

- The German policy must formulate precise development goals and the legislative body must emphasize them by adjusting the law. This includes accelerating approval procedures and the designation of preferential areas in regional planning programs.
- Risk minimization instruments for finding geothermal resources are required. Economically, this can be achieved by significantly increasing state funding for geothermal projects. Technically, the risk can be reduced by geophysical investigation of metropolitan areas, drilling of exploration wells, and the establishment of pilot facilities.
- The industry is challenged to invest in key technologies for the industrial development of geothermal resources. These investments are supposed to be subsidized by the state. Examples are drilling technologies and high-temperature heat pumps.
- Alongside the value chain, five to 10 people are required per MW of installed geothermal capacity. Thus, the comprehensive development of geothermal energy presents great challenges to the job market and educational institutions. It requires the adjustment of curricula, the supply of advanced training, additional educational institutions, and recruitment programs.

[78] Refer to Wien Energie, https://www.wienenergie.at/tiefengeothermie-aspern/ (accessed 15.03.2023)

- A big challenge poses the public opinion on geothermal energy. It requires an expanded public relation program to persuade society of the many advantages of geothermal applications.[79]

The recommended actions to boost shallow geothermal development are very similar to the ones for deep geothermal development:

- Acceleration and simplification of approval procedures are necessary. Geothermal wells that are not deeper than 400 meters should be exempted from mining law approvals.
- Advanced training of 400.000 laborers in the fields of sanitary, heating, and climate craft is urgently required. The focus of this training is on the transition towards renewable heat sources. Also, in the field of drilling, there is an immense lack of skilled personnel. In the short run, 6.000 qualified workers and 2.500 units of drilling equipment are required. Certainly, not only the industry needs qualified personnel in the domain of geothermal energy but also the public authorities. To fight these problems, it needs appropriate education opportunities, recruitment programs, and facilities for career changers.
- The installation of fossil heating applications must be prohibited and existing ones must be replaced by renewable heating applications clearly before 2045. Incentive programs for doing so must be established by the state. A possibility is to free electricity used for running heat pumps from taxes.
- The volume of geological data must be increased. At short notice, public authorities must provide comprehensive data regarding the subsurface up to 200 meters of depth. In the medium term, they should be able to provide comprehensive geological data of the subsurface to a depth of 400 meters.
- Similar to deep geothermal energy, the advantages of heat pumps are not yet widely known among property owners. In many cases, people are discouraged by the relatively high investment costs and do not consider the low long-term operational costs that make the installation profitable. Information campaigns are necessary. Additionally, public buildings should set a good example by utilizing geothermal heat and other renewable heating sources.[80]

Successfully implemented, these recommended actions should enable geothermal energy to become a crucial part of Germany´s heating sector. The target figures presented in the consulted roadmaps only refer to the direct utilization of geothermal energy and do not consider the generation of electricity. This is because the dimension of direct utilization exceeds the one of power production many times and this trend, most likely, will be even more significant in the future. Thus, similar to Austria, mainly the production of heat is of interest when it comes to comprehensive energy supply in Germany.

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[79] Refer to Fraunhofer-Einrichtung für Energieinfrastrukturen und Geothermie IEG und Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ) (2022), page 6 pp.
[80] Refer to Fraunhofer-Einrichtung für Energieinfrastrukturen und Geothermie IEG (2022), page 8 pp.

Goals in figures

Concretely, the installed capacities for deep geothermal applications in 2030 and 2040 are recommended to be 24 GW and 72 GW. With these capacities, a yearly production of 100 TWh respectively 300 TWh of heat would be possible. Based on the current annual heat consumption of 1.400 TWh, around 7% in 2030 and around 21% in 2040 of Germany´s heating energy demand could come from deep geothermal sources. These capacities require the drilling of around 2.000 deep geothermal wells until 2030 and 7.000 to 10.000 deep wells until 2040. With the current situation regarding qualified personnel and available drilling machinery, this quantity of wells is impossible to drill. Therefore, it is necessary to technically and academically train more than 10.000 people per year. Additionally, drilling equipment must be procured urgently.[81]

Generally, Germany´s potential for heat production by geothermal heat pumps amounts to approximately 600 TWh per year. To accomplish the planned goals of Germany´s climate change policy, it is necessary to almost comprehensively exploit this potential. In numbers, this means that in 2030, three million geothermal heat pumps and in 2040, six million geothermal heat pumps need to be installed. When extrapolating the growth of the geothermal heat pump number of the last years, these target figures cannot be achieved. As with deep geothermal applications, this is mainly due to a lack of personnel and technical capacity. Until 2030, more than 1.000 additional drilling equipment and more than 2.500 additional qualified personnel are required. Until 2040, more than 2.000 additional drilling equipment and more than 6.000 additional qualified personnel are required.[82]

[81] Refer to Fraunhofer-Einrichtung für Energieinfrastrukturen und Geothermie IEG und Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ) (2022), page 36 pp.
[82] Refer to Fraunhofer-Einrichtung für Energieinfrastrukturen und Geothermie IEG (2022), page 10 pp.

2.4 Geothermal drilling and geothermal well

So far, only geothermal energy and its utilization have been discussed. In this chapter, the drilling process, which makes the utilization of geothermal energy even possible, is presented. This is because drilling into the ground establishes a transition from the surface to the subsurface geothermal reservoir. At this point, it is important to mention that in the course of this chapter, the drilling process of rather medium-deep to deep boreholes (minimum depth of a few hundred meters) is described. Generally, the more shallow the borehole, the less complex the drilling process is, and the less equipment is required.

To be able to drill, a force in direction of drilling, the rotation of a cutting tool (drill bit), and the output of crushed material is required. Additionally, it is necessary to keep the hole from caving in and prevent undesired access of subsurface fluids into the hole. All these tasks are executed by the drilling rig and its auxiliaries. How the drilling rig works and what a geothermal borehole looks like, are described in this chapter.

2.4.1 Introduction to drilling

Opposite to oil and gas reservoirs that can mainly be found in sedimentary formations, common rock types in deep geothermal reservoirs include granite, granodiorite, quartzite, greywacke, basalt, rhyolite, and volcanic tuff. Therefore, geothermal formations are, by definition, hot, often hard, abrasive, highly fractured, and under-pressured. Additionally, geothermal reservoirs almost always contain dissolved or free carbon dioxide (CO_2) and hydrogen sulfide (H_2S) gases. These gases are corrosive, especially, H_2S limits the materials that can be used as drilling and production equipment. H_2S also presents a serious safety hazard during drilling. These conditions mean that geothermal drilling is usually more difficult and linked with higher costs, compared to standard oil and gas drilling jobs.[83] However, this statement mainly regards deep drilling and not the drilling of shallow geothermal wells.

A precondition of a drilling job is a successful exploration phase. During the exploration, different professionals like geologists and physicists investigate and test the subsurface for potential geothermal reservoirs. The most valuable technique for exploration is seismic prospection.[84] By generating vibrations, seismic waves are generated in the subsurface and their travel time is recorded. Since the velocity of these waves depends on the medium, they travel through, the composition of the substructure can be determined. In case a potential reservoir is identified, and the technical and economic feasibility is confirmed, the drilling phase can be initiated.[85]

[83] Refer to Finger, J.; Blankenship, D.; (2010), page 14
[84] Refer to Bundesverband Geothermie, https://www.geothermie.de/bibliothek/lexikon-der-geothermie/e/exploration.html (accessed: 23.03.2023)
[85] Refer to Oil and Gas Portal, http://www.oil-gasportal.com/upstream/petroleum-exploration/ (accessed: 23.03.2023)

The preparation of a drilling project consists of two separate but closely related parts, namely the planning of the well and the designing of the well. The planning part includes tasks like listing, defining, scheduling, and budgeting all the individual activities required to drill a well. Careful planning is critical for any drilling operation since it will not only minimize cost but will reduce the risk of injury or property damage from unexpected events. Designing means to specifying all the physical parameters of the well. Examples are its purpose (exploration, injection, or production), its depth, and its diameter.

After the planning and designing phase, it can be decided which type of drilling rig is suitable for the project.[86] Different types of drilling rigs exist, in the context of this thesis, rotary drilling rigs and their functionality are of interest and get covered in more detail. Though, it is to be mentioned, that conventional rotary rigs only are used for deep drilling projects. Chapter 2.4.5 briefly introduces alternative and smaller dimensioned drilling machines that are frequently used for geothermal drilling jobs. In Figure 25 a simplified diagram of a rotary drilling process is presented.

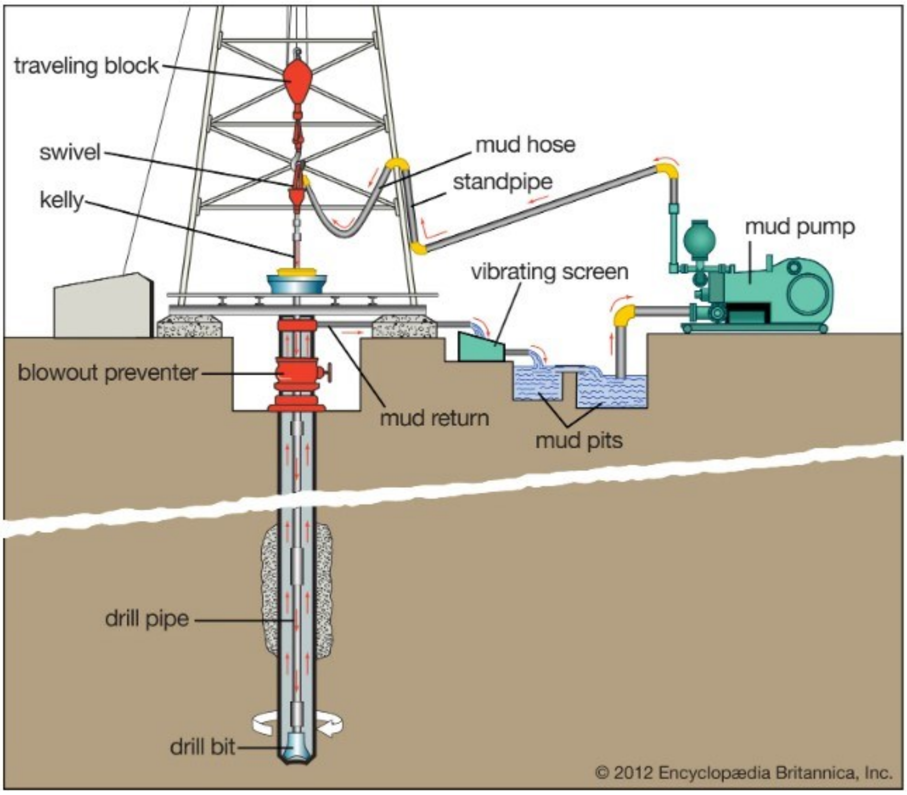

Figure 25: Rotary drilling process[87]

On the bottom of the drill string, which exists of single pipes, is the drill bit. With its metal or diamond cutters, the bit is able to bite into the formation. Thus, when the string rotates and the weight of the pipes is exerted on the drill bit, the formation crushes. As the borehole gets deeper, more pipes need to be added to the drill string. To be able to do

[86] Refer to Finger, J.; Blankenship, D.; (2010), page 20 p.

[87] Source: Britannica, https://www.britannica.com/technology/drilling-mud (accessed: 23.03.2023)

so, the rotation of the string needs to be interrupted. The deeper the borehole, the more compact the rock gets. Hence, more force is needed at the drill bit and this is accomplished by the increasing weight of the drill string. In case the weight of the drill string is not sufficient, very heavy drill pipes called drill collars can be added to the string to increase the weight on the drill bit. The handling of the drill string, thus lifting, lowering, and rotating it, is performed by the drilling rig and its auxiliaries. In order that the hole does not collapse and no undesired fluids enter, drilling fluid, or drilling mud, is pumped downhole within the pipes. The mud not only fills the borehole but travels up towards the surface within the annulus existing between the string and the formation. That way, the mud holds back other fluids from entering, prevents the borehole walls from collapsing, circulates out the debris, and cools and lubricates the bit. At the surface, the mud is relieved from the solids and pumped down again.[88] Located at the top of the well, a tool called blowout preventer (BOP), is placed. This is a large valve that can be closed in case formation fluids enter the borehole, despite the presence of the drilling mud. By closing it, the drilling crew can prevent an uncontrolled release of fluids from the well. After increasing the density of the drilling mud, the BOP can be reopened. When it comes to the safety of the drilling crew, the blowout preventer is one of the most important elements and gets further discussed in Chapter 2.4.4.[89] As can be seen in Figure 25, wells are equipped with a cellar, a dug-out area in which the BOP resides. In most cases, the cellar is cemented and proportioned in a way that the valves of the BOP can be easily reached from ground level. Thus, the purpose of this cavity is the facilitated handling of the equipment but also the collection of fluids spilled from the well.[90]

2.4.2 Introduction to the geothermal well

When wells are drilled to depths of more than a few hundred meters, it is common practice to set successive, separate strings of large-diameter pipes called casings. As the well gets deeper, the diameter of the casings decreases. Therefore, geothermal wells are designed from "bottom-up". This means, the location of the reservoir determines the well's overall length, and the desired flow rate determines the diameter at the bottom of the hole. The well's profile above the reservoir is then set by iteration of the successively larger casing strings. Figure 26 presents a possible design of a geothermal well.

[88] Refer to Marcom, M.R.; (2015), page 1 pp.
[89] Refer to Schlumberger Energy Glossary, https://glossary.slb.com/en/terms/b/bop (accessed: 13.12.2022)
[90] Refer to Schlumberger Energy Glossary, https://glossary.slb.com/en/terms/c/cellar (accessed: 24.03.2023)

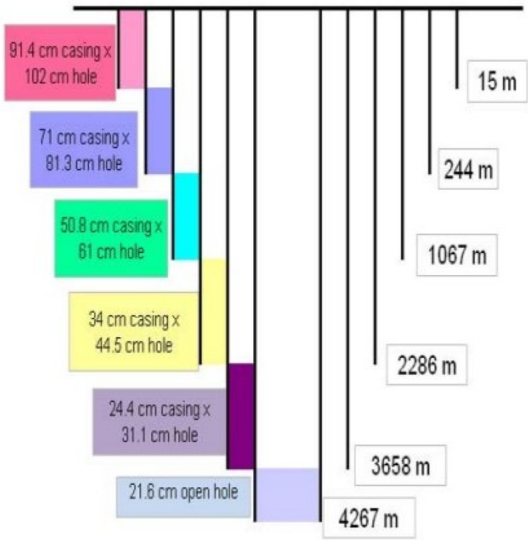

Figure 26: Casing design[91]

There are numerous reasons why setting a casing is necessary. Examples are the protection of aquifers from being contaminated with drilling fluids, the prevention of the formation wall from caving in, and the prevention of formation fluids and pressures from entering the well.

In practice, the well is drilled in sections from the surface to the production zone. Deeper wells are impossible to drill in one section due to differences in formations properties. Thus, each section of the formation, after being drilled, is sealed off by setting a casing string. Such a casing string consists of single pipe joints of approximately 12 meters in length with threaded connections. To make the well even more resilient, the annulus between the casing and the formation is cemented. The cement sheath has the function of preventing fluid communication between producing zones in the borehole and blockading the escape of fluids to the surface. Furthermore, the cement sheath anchors and supports the casing string and protects the casing made of steel against corrosion by formation fluids. Like the drilling mud, the casing is a so-called wellbore barrier and is supposed to help maintain control over the well. Parameters that influence the casing design of a geothermal well are the depth of the reservoir, the desired production rate, the expected subsurface temperature, the chemistry of produced fluid, the well trajectory, and the type of completion. Because geothermal wells produce a relatively low-value fluid, their production rates must be much higher than the ones of oil and gas wells. Hence, geothermal wells not only use casings of relatively large diameters but also directly produce from the reservoir into the casing. For that reason, the casings need to be fitted with corrosion protection on their inside walls. Oil and gas wells mostly produce through a smaller sized production tubing that is installed inside the casing. Well trajectory describes the inclination of a well. Deep geothermal systems often have the feature that their injection and production wells only are a few meters away from each other at the surface, however, underground they run in opposite directions. This is necessary, so the reinjected water does not cool the produced water but can heat up

[91] Source: Finger, J.; Blankenship, D.; (2010), page 16 p.

before being produced again. The planned geothermal plant in Aspern, Vienna, consists of such trajected wells, as Figure 27 images.

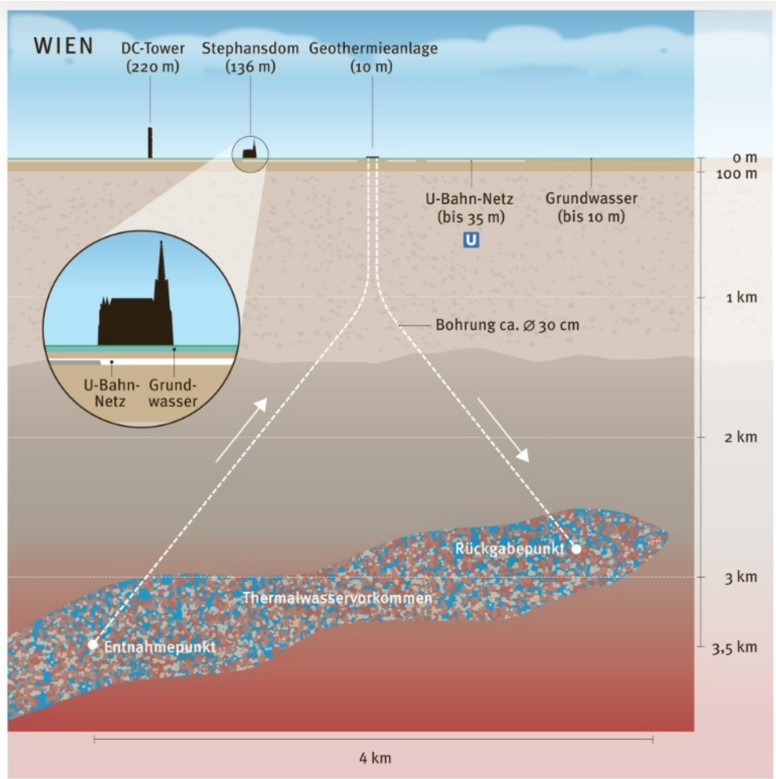

Figure 27: Geothermal power plant in Aspern[92]

2.4.3 Completion of a geothermal well

The term completion refers to the preparation of the well for production. Thus, the completion of a well takes place between the drilling phase and the initiation of production. The reason why completion is briefly introduced in this chapter is that there is a smooth transition from the drilling phase to the completion phase, furthermore, the drilling rig is still required for conducting completion tasks. In case the geothermal well´s purpose is to produce or inject water, the possible completion types are open hole completion and slotted liner completion. Open hole completion means that the casing string does not extend to the bottom of the hole. Slotted liner completion means that a liner with slots is installed in the open hole section at the bottom of the well. Through the slots, production fluid can enter the well.[93] The difference between a casing and a liner is that casings always extend to the surface, a liner only is suspended from inside the

[92] Source: Wien Energie, https://www.wienenergie.at/tiefengeothermie-aspern/ (accessed: 24.03.2023)
[93] Refer to Finger, J.; Blankenship, D.; (2010), page 26 pp.

bottom of the previous casing.[94] However, in case the well is not supposed to produce or inject water but a probe is to be installed, the completion process is different. As already mentioned, a probe can exist of a single loop or of two independent loops that are made of plastic pipes (mostly polyethylene), as Figure 28 presents.

Figure 28: Geothermal probe[95]

Before the probe can be lowered down the borehole, it needs to be filled with water under pressure. That way, its integrity can be tested and the pressure that increases with the borehole´s depth can be compensated. At the same time as the probe gets lowered into the borehole, a string made of hollow metal pipes is descended into the borehole. This string´s purpose is to stabilize the probe while descending as well as acting as a passageway for the bentonite-water mixture which is pumped downwards as soon as the probe is in place. The purpose of backfilling the borehole with bentonite mixed with water is to stabilize the borehole and to maximize the exchange of heat between the probe pipes and the surrounding ground. The injection of the liquid bentonite is performed in several steps, at different levels in the borehole. Between each step, metal pipes are removed to be able to inject higher. Figure 29 presents the installation of a probe existing of two loops and clearly shows the metal string that is lowered into the borehole together with the probe.

Figure 29: Installation of a geothermal probe[96]

[94] Refer to Schlumberger Energy Glossary, https://glossary.slb.com/en/terms/l/liner (accessed: 24.03.2023)
[95] Source: Beodom, https://beodom.com/en/education/entries/geothermal-drilling-and-installation-of-geothermal-probes.html (accessed: 20.04.2023)
[96] Source: Beodom, https://beodom.com/en/education/entries/geothermal-drilling-and-installation-of-geothermal-probes.html (accessed: 20.04.2023)

In Figure 29, it can also be observed that the top ends of the loops have an excess in length, so they can be attached to the surface equipment of the system. Once the borehole is backfilled, the installation of the probe is done and the drilling rig can be moved away. In many cases, the geothermal application exists of more than one probe. Hence, it is required to connect them at a central place. From there, the probes can be brought inside the building for connecting them with the heat pump.[97]

2.4.4 Geothermal drilling site and rig

As can be seen in Figure 30, an entire drilling site not only consists of the rig itself but many other utilities. Hence, the arrangement of the site should be planned carefully, thus the flow of work can be performed not only efficiently but also safely. Typically, companies have standards when it comes to the positioning of various equipment such as water and fuel tanks, generators and engines, mud pits and pumps, solid control systems, pipe racks, and common rooms for the crew. It is of great relevance that none of these elements blocks the emergency escape routes. In case, incidents involving fire or highly toxic gases like H_2S are possible, drilling sites must have a minimum of two designated escape routes that lead in opposite directions, so the crew members can always escape normally to the wind direction. Therefore, wind indicators are set in place and all escape routes lead to muster points that serve as meeting points for the crew.[98]

Figure 30: Rotary drilling rig[99]

[97] Refer to Beodom, https://beodom.com/en/education/entries/geothermal-drilling-and-installation-of-geothermal-probes.html (accessed: 20.04.2023)
[98] Refer to Wirth, S.; (2023), personal communication
[99] Source: Drilling Contractor, https://drillingcontractor.org/looking-beyond-spud-to-release-mapping-out-the-rig-move-process-20340 (accessed: 24.03.2023)

Generally, the standard rotary drilling rig, as it is displayed in Figure 30, consists of the following main elements.

1. Mast and the substructure: Bears the weight of the drill string and provides space to add and remove pipes to the string.
2. Hoisting system: Lifts and lowers the drill string.
3. Rotaries: Rotates the drill string.
4. Power system: Consists of engines that run the drilling rig.
5. Pump system: Handles the circulation of the drilling fluid.
6. Solid control system: Removes the material that the mud delivers to the surface.
7. Well control system: Is responsible that fluids and high pressures cannot escape from the well.

These elements are further discussed in the following chapters.

The mast and the substructure

Within the drilling industry, the mast is commonly named Derrick, even though Derrick and mast are not the same. A Derrick is a semi-permanent structure with its four feet sitting on the corners of the substructure. It must be disassembled to move it. On the contrary, a mast is portable, sits on the rig floor or the ground, and can be folded or telescoped down to be moved.[100] The American Petroleum Institute (API), an eminently respected body in the drilling industry, offers the following definitions for a mast and a Derrick:

- *Mast: A structural tower comprised of one or more sections and then raised to the operating position. If the unit contains two or more sections, it may be telescoped or unfolded during the erection procedure.*
- *Derrick: A semi-permanent structure of square or rectangular cross-section having members that are latticed or trussed on all four sides. This unit must be assembled in the vertical or operation position, as it includes no erection mechanism. It may or may not be guyed.*[101]

Both structures have the same primary function of supporting the immense weight of the drill string. In this thesis, the term mast will further be used in case the type of transport is of no importance.[102]

The part of the drilling rig which stands on the ground and supports the full load of the mast, the rotary table (explained subsequently), the drill string, and the load of the casing when it is suspended in the hole is called substructure. On top of the substructure is the rig floor and the doghouse. The rig floor is where the crew performs activities like adding or removing drill pipes. The doghouse presents an office, a control room, and a shelter at the same time. Via its four legs, sitting on the corners of the substructure, the mast transmits the vertical loads to the substructure and the substructure forwards the loads

[100] Refer to Van Dyke, K.; (2012), page 2 pp.
[101] Refer to American Petroleum Institute (April 2004), page 1
[102] Refer to Van Dyke, K.; (2012), page 2 pp.

via its broad I-beams into the ground. Rigs of smaller dimensions with a telescopic mast, often come on wheeled units. Loads of these rigs are supported by jacks under which plates or beams are inserted. These jacks release the wheels of the unit from the loads and, hence, pose as a substructure for wheeled rigs. Generally, it is of great importance to distribute the vertical loads exerted on the ground, so the ground can withstand them as long as the rig is in place. Besides the function of bearing massive loads, the substructure elevates the rig floor from the ground and, therefore, creates space for the blowout preventer. The blowout preventer is an indispensable element in drilling operations. Either it is positioned within the substructure, a cellar where it fits in is available, or it is a combination of both. The first option makes operations much easier for the drilling crew.[103]

Figure 31 displays a substructure. It is obvious that the substructure widely rests on the ground, so the distribution of the heavy loads is possible. Also displayed is the stair for the workforce to access the rig floor and the pipe ramp over which the pipes are pulled on the rig floor.

Figure 31: The substructure[104]

When it comes to the mast, this component is rated by the vertical load it can carry and the wind velocity it is capable to withstand. Figures vary broadly between 60 and 1.134 tons of bearing capacities and between 160 and 210 kilometers per hour of wind velocities the masts can endure. Another important parameter for masts is the height, which can be more than 50 meters and decides how many pipes can be manipulated by the crew at the same time.[105] The mast´s height is measured from the drilling or working

[103] Refer to Drilling Manual, https://www.drillingmanual.com/derrick-drilling-rig-oil-gas/#substructures (accessed: 16.11.2022)
[104] Source: Rig Yard, https://rigyard.com/wp-content/uploads/2019/03/IMG_2110.jpg (accessed: 27.03.2023)
[105] Refer to Marcom, M.R.; (2015), page 18

floor to the crown block. How many pipes the rig can add to or remove from the drill string depends on the clear height. It is important to account for the clear height because not the total height of the mast is available for handling pipes. Common pipes are between eight and 10 meters long, so a mast that can handle a joint of three pipes has a clear height of approximately 30 meters.[106]

Different types of masts exist, examples are the “Pull-type”, the “Push-type”, and the Bootstrap type. The “Pull-type” and the “Push-type” masts differ in the way they get erected on site, whereas the names already reveal how this is conducted. Before the erection, the mast gets completed in the horizontal position and, for safety reasons, all objects that can drop during the erection are removed. In the context of this thesis, workover units, which are a subcategory of the “Push-type”, are of interest. Hydraulic cylinders enable the erection of the “Push-type”- mast. Figure 32 presents the erected mast of a workover unit.

Figure 32: Workover unit[107]

The Bootstrap mast usually fulfills the criteria of a Derrick, meaning that it needs to get assembled and disassembled for every single project and cannot be transported in its entirety. The components of the mast are delivered in pieces by trucks, the erection is then performed by heavy cranes, forklifts, and other heavy machinery.[108]

[106] Refer to Drilling Manual, https://www.drillingmanual.com/derrick-drilling-rig-oil-gas/ (accessed: 16.11.2022)
[107] Source: Well Plugging, https://wellplugging.com/equipment/workover-rigs (accessed: 27.03.2023)
[108] Refer to Wirth, S.; (2022)

The hoisting system

The hoisting system´s main task is to lift the drill string in and out of the borehole. This system consists of the substructure, the mast, the drawworks, the blocks, and the drilling line, however, the substructure and the mast were already covered separately. As illustrated in Figure 33, the crown block, the traveling block, the fastline, and the deadline, which are both sections of the drilling line, form a large set of pulleys.

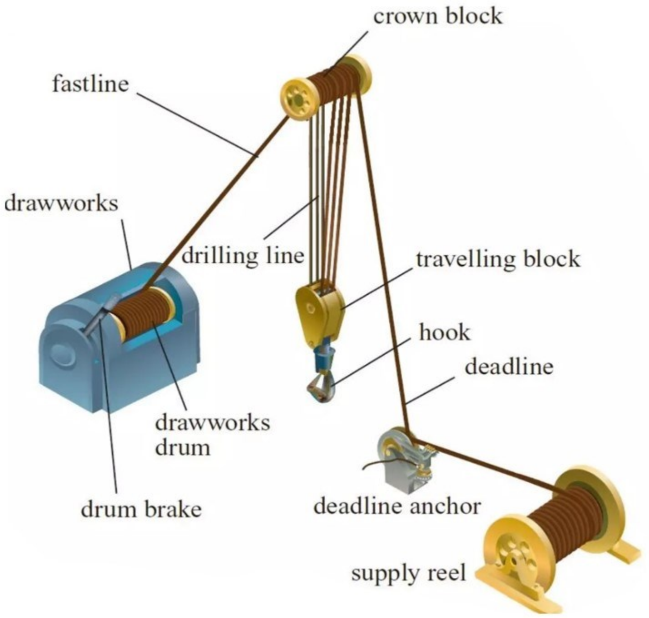

Figure 33: The hoisting system[109]

This arrangement of pulleys supports the full load of the string. The drawworks is a large winch that spools in and out the drilling line, hence it is ultimately responsible for moving the drill string. On the rig, the drawworks are often the heaviest, largest, and also the most expensive machinery. Attached to the drawworks, is the rig´s brake system, which is responsible for controlling the movement of tons of drill pipe. The drilling line is a braided wire rope consisting of steel wires. The components and the functionality of the hoisting system are explained based on the drilling line´s course. Starting point is the supply reel from where the drilling line runs over the deadline anchor to the crown block. The deadline anchor, positioned at or underneath the rig floor, firmly clamps the drilling line, so it is stationary between the anchor and the crown block, thus called deadline. The crown block is installed at the top of the derrick and contrary to the traveling block stationary. It consists of a large configuration of four to seven sheaves, that are mounted on a central axle. The purpose of the sheaves is to transfer the load of the drill string from the drawworks through the drilling line to the structure of the mast. These sheaves can have a diameter wider than 1,5 meters and have grooves through which the drilling

[109] Source: Slide Share, https://www.slideshare.net/EngElsayedAmer/rig-components-86164430 (accessed: 28.03.2023)

line can run. Between the crown and the traveling block, the drilling line is alternately reeved over their sheaves until the desired number of lines is achieved. Usually, rigs have six or eight such lines, however, rigs intended for drilling deep wells can have up to twelve lines. The higher the number of connecting lines between the blocks, the higher the hoisting power of the rig. The last line reeved over the crown block sheaves runs down to the drum of the drawworks, where the drilling line is wrapped around several times. When lifting or lowering the drill string, it moves faster than any other part of the drilling line, that is why it is called fastline. With every progressive sheave, the relative speed of the drilling line declines.[110] The traveling block, connected via several lines, hangs down from the crown block and can move within the mast´s structure. Mounted on the traveling block it is the hook to which components of the rig´s rotating system are attached. The hook supports the full load of the drill string. Similar to the crown block, the traveling block is also an assembly of sheaves but protected by a metal housing. This housing prevents any exposed parts of the block from hitting other components of the rig while moving up and down inside the mast.[111]

The rotary system

The rotary system of a drilling rig performs the following three jobs simultaneously:

- Provide the rotating force to the drill string and drill bit.
- Offer a passageway for the drilling mud to travel downhole.
- Allow the drill string´s weight to press down on the bit to make it drill.

The fact that rotary drilling allows these tasks to be fulfilled simultaneously, let it stand out compared to other types of drilling. Nowadays, there are two different forms of rotary drilling that differ in the rotary tools that are applied. There is the conventional rotary drilling system (Figure 34) and the top-drive rotary drilling system (Figure 35).

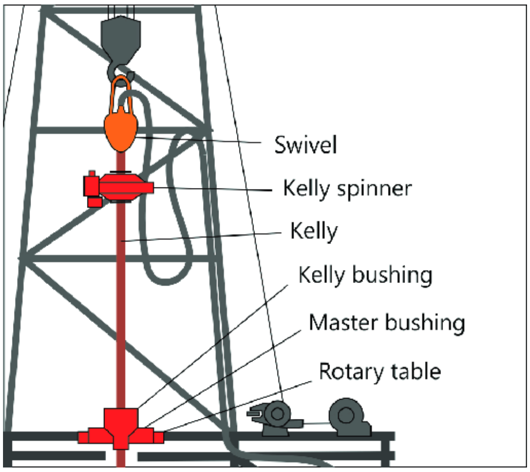

Figure 34: Conventional rotary drilling system[112]

[110] Refer to Marcom, M.R.; (2015), page 17 pp.
[111] Refer to Davis, L.D.; (2014), page 84 pp.
[112] Source: Research Gate, https://www.researchgate.net/figure/Rotating-equipment-of-the-drilling-rig_fig5_322987413 (accessed: 28.03.2023)

Simplified, the conventional rotary drilling system´s functionality looks as follows. The rotary table assembly is a rotating machine integrated into the rig floor, as Figure 34 shows. It can either be driven mechanically or electrically, rotates, and transfers this motion to the kelly while drilling. As displayed in Figure 34, the rotary table assembly comprises the master bushing and the kelly bushing. The rotary table cannot directly rotate the kelly but needs the bushings to transfer the motion to the kelly. The master bushing is a robust steel cylinder that sits inside the rotary table and in turn, rotates the kelly bushing that is attached to it. The kelly is a pipe and its shape of four or six flattened sides fits perfectly into the kelly bushing´s shape. When the rotary table starts to rotate, it rotates the kelly and the kelly rotates the drill string since they are joint at their ends. At the top end, the kelly is linked to the swivel. The swivel can be defined as a device that joins two parts and permits one or both of these parts to rotate freely. At the upper end, the swivel gets attached to the hook and at the other end, it gets joint with the kelly. That way, the swivel supports the weight of the drill string during drilling and allows the kelly to rotate while the hook does not. On top, it provides a passageway for the drilling mud to enter the drill string through the kelly. When drilling is stopped, for example, to add or remove pipes, the drill string is detached from the hook and must, therefore, be held alternatively. In this case, the drill string is suspended from the rotary table, thus, the rotary table supports the string´s weight. For that purpose, a device called slips is placed into the master bushing that grips the pipe and holds it in place.

Drilling rigs that do not use conventional rotary drilling systems use a top drive system instead. The top drive hangs from the hook, is equipped with a very powerful motor, and synergizes the functions of the rotary table, the kelly, and the swivel. This is possible because the upper end of the drill string is threaded into the drive shaft of the top drive. That way, the kelly and the swivel are replaced, however, the rotary table is still required to support the drill string´s weight when pipes are added or removed. Summarized, the functions of the top drive are the rotation of the string, the supply of a passageway for the drilling mud, and the support of the drill string´s weight. Figure 35 displays a top drive hanging in the mast.[113]

[113] Refer to Davis, L.D.; (2012), page 1 pp.

Figure 35: Top drive[114]

The power system

The drawworks, the rotaries, the pumps, and much more equipment need power to fulfill their tasks. However, not all of these systems are outfitted with separate engines but are provided with power from the rig´s power station. Usually, the power station consists of several powerful diesel engines and is positioned at a selected area at the drilling site. Diesel engines are internal combustion engines that take in air and diesel and burn this mixture to create energy to do the work. Diesel is stored in tanks at a designated area on the drilling site. The transmission of power from the power station to the equipment can either be done mechanically via machinery or electricity. Nowadays, electrical transmission is the most common form. Mechanical transmission means that the diesel engines are equipped with couplings that connect them to the machinery. The machinery consists of heavy-duty sprockets and chains and is called the compound. The power is transferred from the engines to the compound and from there it is forwarded by sprocket and chains to the according equipment. When the transmission takes place electrically, a large generator is attached to every engine. These generators are driven by diesel combustion engines and produce electricity. Through heavy-duty cables, the electricity is sent to powerful electric motors mounted on or next to the various equipment needing the power.[115]

[114] Source: Drilling Contractor, https://drillingcontractor.org/cant-keep-the-offshore-industry-down-22460 (accessed: 28.03.2023)
[115] Refer to Baker, R.; (2015), page 1 pp.

The pump system

To be able to establish the connection between the reservoir and the surface, so to drill a hole, three systems are required. Namely, these are the rotating system, the hoisting system, and the circulating system. The circulating system´s job is to ensure wellbore stability and prevent formation fluids to enter the wellbore, to clean the bottom of the wellbore and transport cuttings to the surface, and to cool and lubricate the drill bit. A typical circulating system consists of drilling mud, equipment that moves the mud, and devices that clean and condition the mud. The rig´s pump system is responsible for moving the drilling mud within the circulating system. Figure 36 images a typical circulating system.

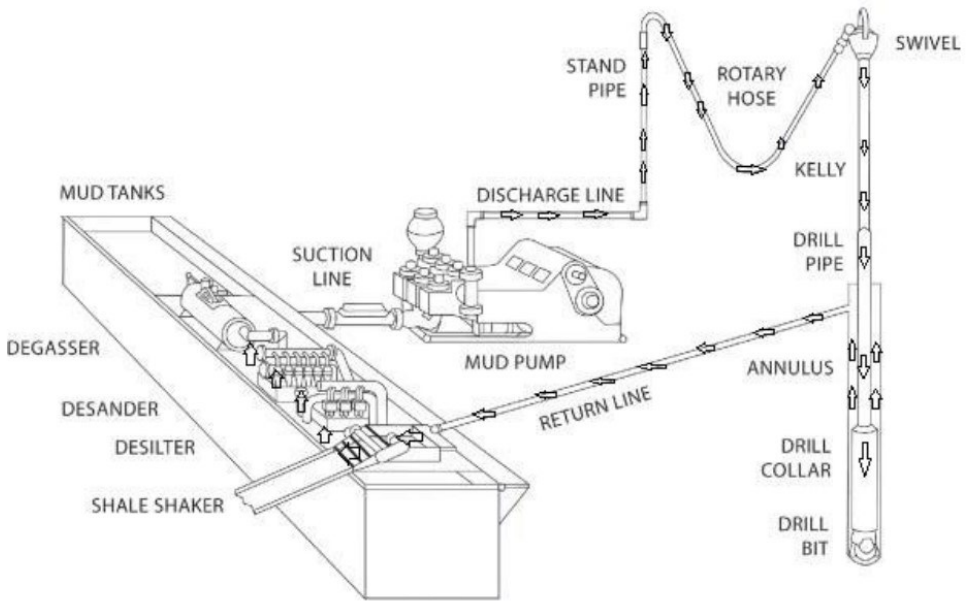

Figure 36: Circulating system[116]

The elements that are pictured on the left side of Figure 36 are responsible for conditioning the mud and are introduced in Chapter 2.4.4. The mud pumps are the heart of the circulating system. In case the pumps fail, drilling cannot be proceeded and must be put on a halt. Hence, mud pumps are built very sturdy, can handle enormous loads, and resist abrasive fluids. Normally, a minimum of two heavy-duty mud pumps and a few smaller auxiliary pumps are applied in drilling operations. Mud pumps are reciprocating pumps, while auxiliary pumps are mainly centrifugal pumps. Reciprocating describes the working principle of the pump, as a piston in a cylinder moves back and forth. By this reciprocating movement, the drilling mud is displaced. Centrifugal pumps have no pistons but transfer energy to a liquid through a rotating impeller. Purposes for using a centrifugal pump are various, instances for possible applications are moving water to mix

[116] Source: Research Gate, https://www.researchgate.net/figure/Drilling-mud-circulation-system-McBride-2012_fig2_339882289 (accessed: 28.03.2023)

mud, mixing cement, washing down equipment, or cooling the brakes of the drawworks. Compared to reciprocating pumps, the centrifugal pump is smaller, quieter, and less expensive. Centrifugal pumps can transfer large volumes of liquid, but they do not develop pressure much higher than 10 bar. This is far less than reciprocating pumps are capable of and what is required for pumping mud through the system.[117]

The solid control system

Besides the drilling mud itself and the pump system, the solid control system is the third existential part of the circulating system. This system takes care of cleaning and conditioning the mud. This is a vital job since the mud returns from the hole containing cuttings, sand, impurities, and purposely added solids. If not removed, these undesired properties increase the mud´s viscosity which causes pumping issues. Additionally, the solids increase wear on the circulating system´s equipment and slow down the drilling rate. The main components of the solid control system are the mud tanks, the shale shaker, the degasser, the desander, and the desilter. These elements are all depicted in Figure 36.

As can be seen in Figure 36, the mud enters the shale shakers at first and is then processed to the desilter, desander, degasser, and mud tanks, before being pumped back downhole. This order of solid control elements is used at most drilling sites. Stagewise, coarse particles get separated at first and by each step, finer particles are sorted out, so clean mud arrives at the tanks. Between the different mud treatment elements, pumps, mostly centrifugal ones, process the mud further.

First in the mud treatment line are the shale shakers. Their task is to remove cuttings from the mud. A shale shaker consists of one or more vibrating and/or rotating screens with openings that allow the mud to flow through but prevent solids of a certain size to fall through. The screens are made of heavy wire with square, rectangular, or hexagonal openings. The mesh size of a screen is a key parameter of the shale shaker´s performance and is measured in openings per inch (ca. 2,5cm). A high screen mesh, therefore, has very small but many openings and only allows very fine solids to pass through. When drilling, shale shakers are always operating.[118]

The next mud treatment components that are in line after the shale shakers are desanders and desilters. Their task is to separate solids from the mud that passed the shakers. As their names imply, the desander is supposed to remove sand, while the desilter removes finer particles or silt. Both use hydrocyclones as a separation mechanism. A hydrocyclone has the shape of a cone and is outfitted with a mud inlet on one side, a mud outlet (overflow) at the top, and another outlet (underflow) for solids at the bottom. This can be seen in Figure 37.

[117] Refer to Van Dyke, K.; (2013), page 1 pp.
[118] Refer to Van Dyke, K.; (2013), page 146 pp.

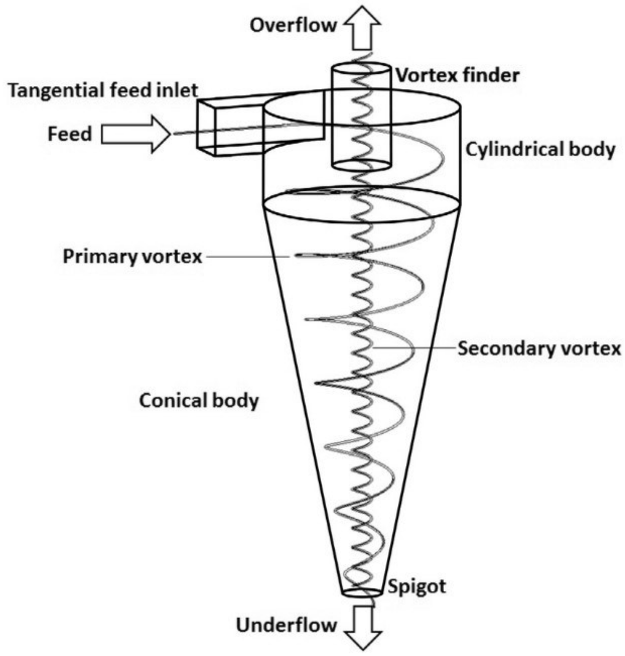

Figure 37: Principle of a hydrocyclone[119]

During drilling, a centrifugal pump pressures the mud through the inlet of the cone, which is not perpendicular but tangential to the side of the cone. So, the mud strikes the curve of the cone and starts to whirl. This whirling motion of the mud inside the hydrocyclone is like a vortex. The vortex finder, a short pipe, extends into the cone´s body just below the feed inlet and forces the vortex downwards. Due to centrifugal forces, larger and heavier mud components are thrown toward the cone´s wall, while finer particles move outward more slowly and remain as part of the fluid mud in the cone´s center. The larger particles and a small amount of fluid are traveling downwards the cone until they exit through the outlet at the bottom. This is marked as the primary vortex in Figure 37. At the same time as the primary vortex moves downwards, the secondary vortex, consisting of fluid and very fine particles, reverses direction, spirals upwards, and leaves the cone through the overflow, or mud outlet. The reason, why the secondary vortex changes direction is the increased pressure at the bottom of the cone. The smaller the cones and the more are installed in a unit, the finer the solids that can be removed. Diameters of desander cones vary between 15,2 cm to 30 cm, while desilter cones have diameters between 7,6 cm and 12,7 cm. Usually, desanders have one to three cones, while desilters house between eight and 20 cones.[120]

The last mud treatment equipment in line is the degasser. A degasser is a completely closed vessel or tank made of steel. The purpose of this device is to remove gas from the mud and vent it at a safe distance from the well. Removing gas from the mud is necessary since the gas is manipulating the composition of the mud, especially making the mud much lighter. Because the mud´s weight is crucial, the gas must be removed

[119] Source: Research Gate, https://www.researchgate.net/figure/Schematic-hydrocyclone-showing-the-main-parts-and-streams_fig1_325613068 (accessed: 29.03.2023)
[120] Refer to Van Dyke, K.; (2013), page 154 pp.

from the mud before it is pumped back into the borehole. Gas mixes with the mud when the drill bit enters a formation containing small amounts of gas.[121] The working principle of the separation is based on the distribution of the mud as a thin film in the tank. Within this thin film, entrained gas bubbles expand, come to the surface, break, and are sucked in by a vacuum pump. The gas is transferred through a discharge line, while the degassed mud exits the tank and is further transferred to the mud tanks.

Finally, the treated mud enters the mud tanks before being pumped back into the borehole. Summarized, the tanks are responsible for supplying mud to the mud pumps, receiving treated mud, storing reserve mud, allowing the mud to cool off, and serving as a reservoir where additives can be mixed into the mud. Usually, a mud circulating system includes a minimum of two tanks that have a known volume, so chemical treatment of the mud is facilitated.[122] As the mud resides in the tanks, solids can settle on the tank´s bottom. Since this effect is completely undesired, it is important to keep the mud in the tanks in motion. Therefore, jet guns and agitators are installed to stir the mud.[123]

The well control system

Well control is key when it comes to the safety of the drilling crew and the well´s surrounding area. In case of losing control over the well, a blowout can take place, which in turn is the result of a kick. Besides fatalities and injuries among the crew, blowouts can also cause catastrophic environmental and economic damage, hence needing to be prevented at all costs. Because the three terms well control, kick, and blowout are of such importance, definitions are presented:

- *Well control: Activities implemented to prevent or mitigate an unintentional release of formation fluids and gases from the well to its surroundings.*[124]
- *Kick: Influx of reservoir fluid into the wellbore during drilling or workover that results in shutting in the well and increased pressure below the shut-in device (usually a BOP).*[125]
- *Blowout: Uncontrolled flow of well fluids and/or formation fluids from the wellbore to the surface or into lower pressured subsurface zones (underground blowout).*[126]

By applying an accurate combination of well barriers, well control and integrity can be achieved. These barriers can be distinguished into primary barriers and secondary barriers. The primary barrier is directly exposed to formation the fluid pressure. In case the primary barrier fails, the secondary barrier assures control over the well. Factually, the primary barrier during drilling is the fluid column of the drilling mud. Its hydrostatic pressure should be able to hold back formation fluids. The most important requirement for this job is the correct density of the drilling mud. If gas or other formation fluids can enter the wellbore despite the presence of the mud column, it is on the secondary barriers

[121] Refer to Van Dyke, K.; (2013), page 172 pp.
[122] Refer to Van Dyke, K.; (2013), page 23
[123] Refer to Van Dyke, K.; (2013), page 181 pp.
[124] IADC, https://iadclexicon.org/well-control/ (accessed: 29.023.2023)
[125] IADC, https://iadclexicon.org/kick/ (accessed: 29.023.2023)
[126] IADC, https://iadclexicon.org/blowout/ (accessed: 29.023.2023)

to prevent the intruding fluids from escaping to the surface. The most prominent secondary barrier is the blowout preventer (BOP), other examples are the casing or the casing cement.[127]

So, a blowout cannot take place as a consequence of a kick, the drilling crew must detect the kick in time. Indications for a kick are rising mud levels in the mud tanks, increasing volume of mud flowing from the well, and mud flowing from the well despite turned-off pumps. Once the kick is detected, the crew must take corrective measures against it, hence activating well control equipment which consists of the BOP, the chokes and the choke manifold, the accumulator, and the poor boy.[128]

Blowout preventers, among other equipment, are applied to close in a well and control a kick before it results in a blowout. BOPs are installed on top of the well, inside the cellar. Usually, several BOPs are mounted on top of each other and form a combination called a blowout preventer stack.[129] These stacks are classified by their working pressures and the higher the pressure is, the larger the stack´s height needs to be. Figure 38 presents a typical BOP stack with its numerous components. However, the arrangement of components can vary broadly and needs to be correlated with the well´s specifications.

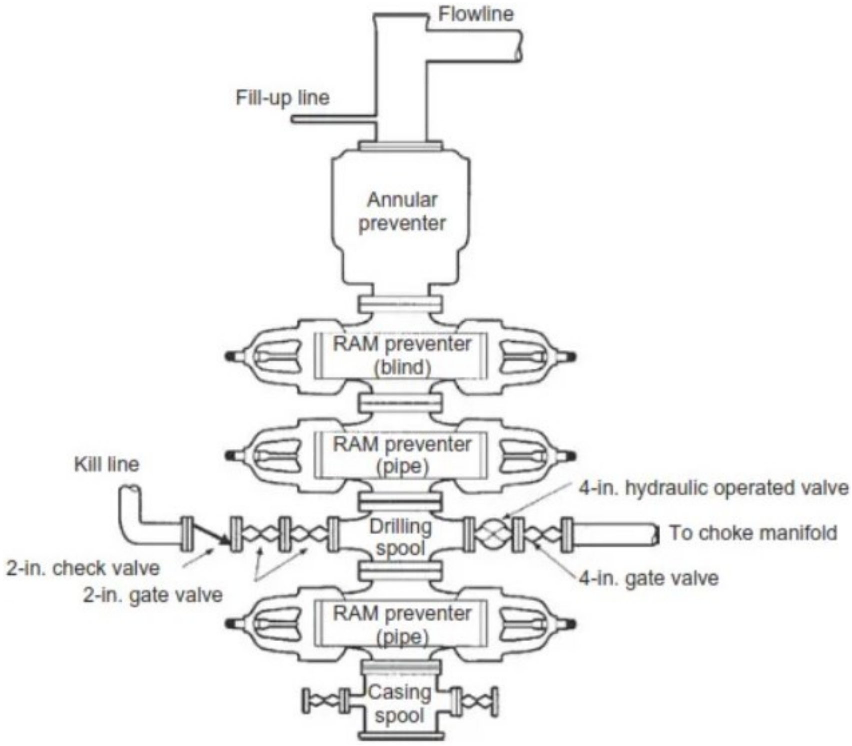

Figure 38: Blowout preventer stack[130]

When looking at Figure 38, it is visible that on top of the stack, an annular preventer is installed, followed by several different types of rams. Additionally, several spools on the

[127] Refer to Bundesverband Erdgas, Erdöl und Geoenergie e. V.;(2015), page 6 pp.
[128] Refer to Marcom, M.R.; (2015), page 63 pp.
[129] Refer to Marcom, M.R.; (2015), page 65
[130] Source: Drilling manual, https://www.drillingmanual.com/bop-blowout-preventer-stack-arrangements-types/ (accessed: 30.03.2023)

BOP´s sides enable the crew to connect tubings to circulate out a kick, even though the well is shut in.[131] The annular preventer is able to seal around any object with a circular, or almost circular, cross-section as well as over an empty hole. Besides the drill string, it can also seal around a hexagonal and a square-shaped kelly.[132] Ram preventers are large steel valves that seal the well by forcing a set of rams together from two sides. In total, four different types of rams exist, which are the blind ram, the shear ram, the pipe ram, and the variable bore ram. These different rams vary in their inside, fulfill different tasks, and can be united in a BOP stack. The blind ram can close an open hole, the shear ram can cut the pipe and close the hole completely, and the pipe ram can close around a pipe but cannot close an open hole. The variable bore ram operates similarly to the pipe ram, just a bit more flexible when it comes to the diameter of the pipes, however, not as flexible as an annular preventer.[133] The whole BOP stack is activated by hydraulic power. The hydraulic fluid is stored under pressure in the accumulator to which the BOP stack is linked via high-pressure lines. On onshore drilling sites, the accumulator is positioned at least 15 meters away from the rig due to safety reasons.[134] The preventer stack and the corresponding accumulators are operated from an electric control panel located on the rig floor. However, to be able to activate the preventer, levers at the accumulator unit must be switched in addition to initiating it from the control panel.[135]

The choke manifold is an arrangement of valves, fittings, and lines that provide flow routes to control exiting fluids from the well when one or more preventers are closed. Chokes are valves that control fluid pressures in a sealed system. From the BOP stack the fluids arrive at the manifold via the choke line, which is pictured in Figure 38. Besides providing flow routes, the manifold´s purpose is to exert back pressure on the well. Back pressure is generated and controlled by adjusting the choke´s opening sizes. The smaller the opening size of the choke, the higher the back pressure. This pressure prevents the invasion of further formation fluids into the well. Finally, when leaving the manifold, the fluid´s pressure should be reduced to atmospheric pressure. Figure 39 presents a typical choke manifold.

[131] Refer to Wirth, S.; (2022)
[132] Refer to Drilling Manual, https://www.drillingmanual.com/bop-blowout-preventer-stack-arrangements-types/ (accessed: 30.03.2023)
[133] Refer to Wirth, S.; (2022)
[134] Refer to Marcom, M.R.; (2015), page 69
[135] Refer to Wirth, S.; (2022)

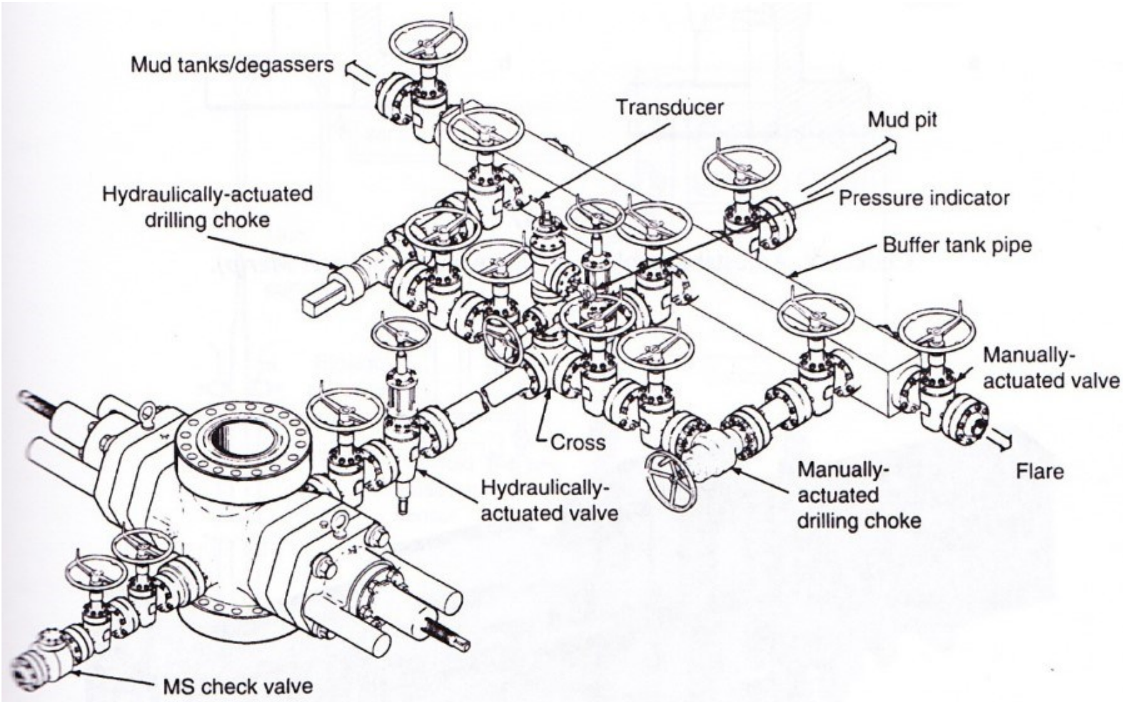

Figure 39: Choke manifold[136]

Practically, when a kick occurs, closing one or more of the blowout preventers is only the first step. Next, the drilling crew opens the choke and the kill line that are attached to the BOP stack. Through the kill line, heavy drilling mud is pumped downhole by the mud pumps. The heavy mud is supposed to balance formation pressure and circulate out the undesired formation fluids. Simultaneously, if the chokes are adjusted correctly and appropriate back pressure is produced, mud and kick leave the well through the choke line but no more formation fluids are entering the well.[137]

The last element that needs to be mentioned in the context of well control procedures is the mud gas separator or more commonly named poor boy. Its design and its purpose are similar to a degasser. The poor boy also is a completely closed steel tank, however, it can separate much higher gas quantities from the mud than a degasser is capable of. In case of a kick, the well is closed in and the mud-containing gas is sent to the mud-gas separator. The composition and working principle of a poor boy is quite simple. It is a vertically standing vessel with numerous baffle plates inside. When the mud enters through the inlet, it can spread out on the baffle plates, hence, increasing its surface area. As the mud flows down the plates, the entrained gas breaks out and moves upwards due to its lower density than the surrounding atmosphere. On the vessel´s top, a vent line is installed through which the gas exits the vessel and gets flared at a safe distance from the well. At the same time as the gas leaves the vessel, degassed mud flows down the plates, exits the vessel on the bottom, and enters the mud return line

[136] Source: Fundamentals of Onshore Drilling, http://geologie.vsb.cz/DRILLING/drilling/theory.html (accessed: 30.03.2023)
[137] Refer to Marcom, M.R.; (2015), page 71 p.

leading to the mud treatment components. It is important to mention that a poor boy only operates in the event of a kick and is not part of the usual mud treatment operation.[138]

2.4.5 Alternative drilling rigs and procedures

As already stated, conventional rotary drilling rigs are mainly used for medium-deep and deep drilling projects. However, for certain geothermal drilling projects, for instance, shallow geothermal wells, different procedures, and different machines need to be applied. In this chapter, selected alternative drilling possibilities are briefly introduced.

Especially, for drilling shallow geothermal wells of only a few hundred meters deep, drilling machines of smaller dimensions than conventional rotary drilling rigs are used. Nevertheless, they apply the same technique as their bigger relatives, namely the rotary drilling method including the application of drilling mud. In many cases, these drilling machines originally were designed for drilling water wells, however, nowadays are also used to drill shallow geothermal wells. These drilling machines are either arranged on a truck or a crawler chassis, thus are mobile.[139] Figure 40a and Figure 40b present examples of a drilling site of a shallow geothermal project respectively a drilling machine of smaller dimension.

Figure 40a and 40b: Shallow geothermal drilling sites and machines[140]

[138] Refer to Van Dyke, K.; (2013), page 173 pp.
[139] Refer to Nordmeyer (2002), page 2 pp.
[140] Source: KDS GmbH, https://www.kds.co.at/leistungen/tiefenbohrung-und-erdwaerme/ (accessed: 19.04.2023)

When regarding Figure 40a and Figure 40b, some parallels but also some differences to conventional rotary drilling sites are obvious. Even though it is of a smaller dimension, a circulating system, including mud pumps and mud tanks, is present. In most cases, the solid control system only consists of a mesh that divides the mud tank into two separate parts. This way, the solids can be segregated and are continuously removed from the tank, thus are not pumped back into the borehole. It needs to be mentioned that in the course of shallow geothermal projects, sometimes water is used instead of drilling mud.[141]

When looking at the mast of the machine, it is obvious that it is not pyramidally shaped but is a vertically standing mast. Therefore, these masts can only bear a fraction of the weight that the masts of conventional rotary rigs can withstand. Because of that limitation, most of these small drilling machines are capable of only drilling a maximum of 300 meters deep. For deeper wells, they are not able to bear the weight of the drill string.[142] Normally, the masts of such machines have a maximum height of 10 meters.[143] However, there are exceptions to this type of drilling machine which are capable of drilling much deeper than 300 meters, because their masts can bear more weight. An example is the DSB5/50 from the German drilling machine producer Nordmeyer. This machine can bear 50 tons of hook load, hence, can drill to depths of around 1.500 meters.[144] Figure 41 presents a diagram of this type and additionally displays its measures.

The drill string, when applying this type of drilling machine, can be rotated by a small rotary table or by a rotor head to which it is attached at its top.[145] Figures 40a, 40b, and 41 present the latter option which is the most common driving mode for small drilling machines. Nowadays, the rotating head often is a power swivel. A power swivel simply is a swivel with an internal motor installed. The motor rotates the swivel and the swivel in turn rotates the drill string.[146] Simultaneously, drilling mud is pumped into the drill string through the power swivel or rotating head. As can be seen in Figures 40a, 40b, and 41 the rotating head is directly attached to the mast, where it can move vertically. This is another difference from the conventional drilling rig, where it hangs from the drilling line. On the bottom of the mast, equipment for retaining the drill string and screwing pipes is arranged. The different elements of these small drilling machines are mostly driven by hydraulic power.[147] Equipment that is not applied for shallow geothermal drilling jobs is the BOP, the choke manifold, or the poor boy. No well control elements are present at the site. Certainly, well control equipment is required when drilling deeper than a few hundred meters.

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141 Refer to YouTube, https://www.youtube.com/watch?v=nnqdUQo7cWQ (accessed: 19.04.2023)
142 Refer to Nordmeyer (2002), page 3
143 Refer to Nordmeyer (2000), page 2
144 Refer to Handke Brunnenbau GmbH, https://www.handke-brunnenbau.de/unternehmen/ (accessed: 10.05.2023)
145 Refer to YouTube, https://www.youtube.com/watch?v=nnqdUQo7cWQ (accessed: 19.04.2023)
146 Refer to YouTube, https://www.youtube.com/watch?v=zO3gcJnA4-k (accessed: 19.04.2023)
147 Refer to Nordmeyer (2000), page 1

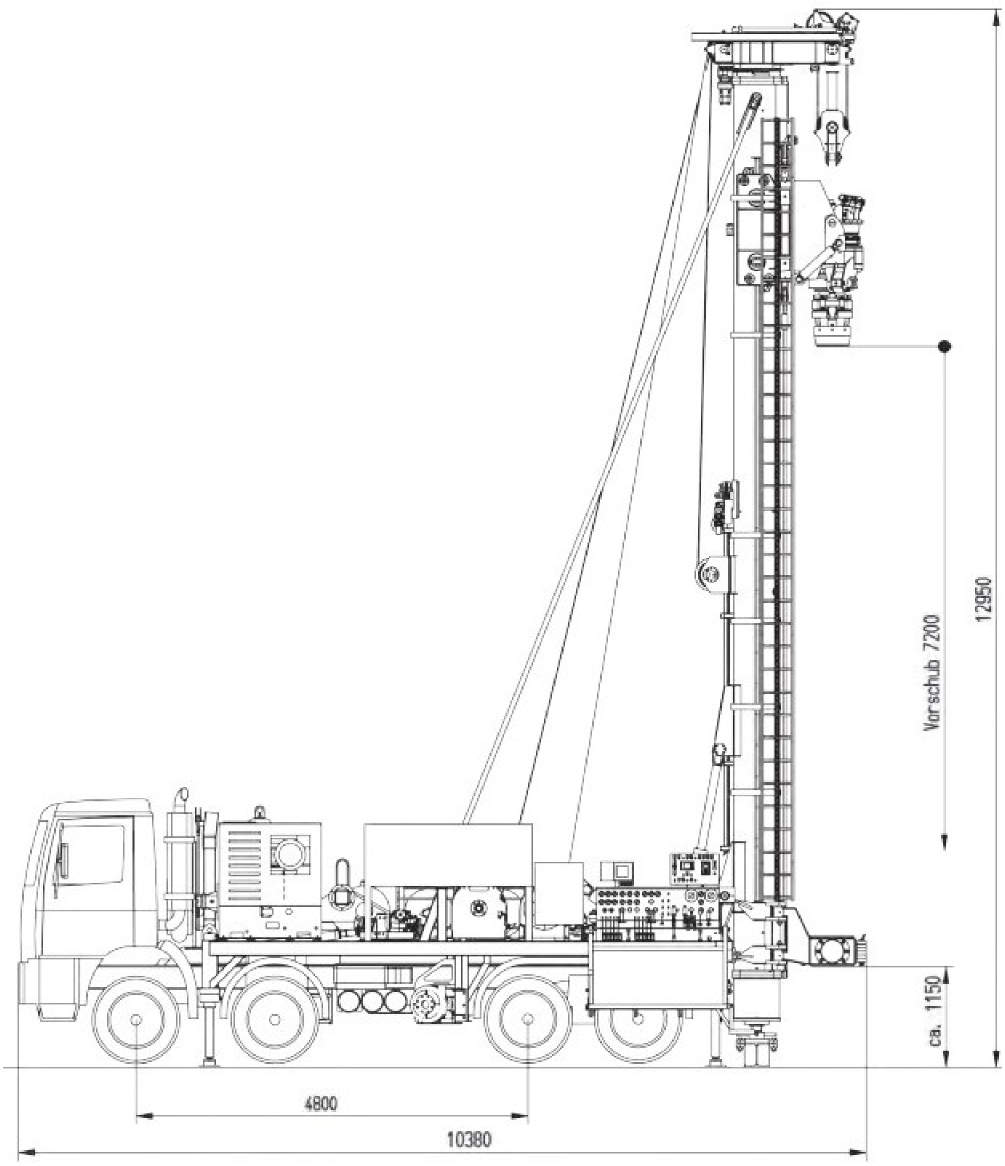

Figure 41: Diagram of a DSB5/50 drilling rig[148]

A special technique that is often applied in geothermal drilling projects is the so-called down-the-hole drilling (DTH) method. Especially, the smaller machines that have just been introduced often use the down-the-hole drilling method. When applying this technique, the drill string is fitted with a hammer at its lower end. The hammer is mounted on the drill bit and comprises a piston that punches the drill bit into the rock. Thus, the drill bit is rotating and impacting simultaneously.[149] This piston is activated by compressed air, which is supplied by a compressor at the surface. From the compressor, the compressed air enters the drill string through the swivel and is then transmitted through the drill pipes to the piston. The compressed air not only drives the piston but

[148] Source: Nordmeyer (2013), page 4
[149] Refer to Furukawa Rock Drilling USA, https://frdusa.com/what-is-dth-drilling/ (accessed: 20.04.2023)

also generates a flushing current that collects the loosened drill cuttings at the hole bottom and conveys them upwards.[150] To better understand this technique, Figure 42 displays a diagram of it.

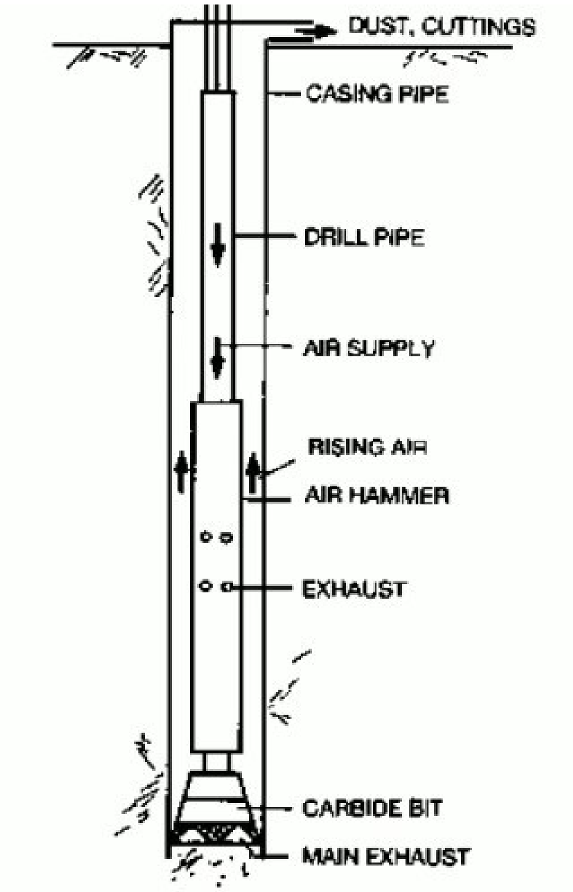

Figure 42: Down-the-hole drilling diagram[151]

The reason why this technique is very efficient is the fact that through the hammering action, the weight on the drill bit can be increased significantly. For instance, when drilling with an 8 3/4 inches (ca. 22,2 cm) diameter bit, the required weight on bit in the case of hammer drilling is 4,5 tons, while at least 18,5 tons are required when rotary drilling, to achieve the same rate of penetration.[152] The rate of penetration is the speed at which the drill bit can crush the formation and thus deepens the wellbore. Usually, this speed is reported in the unit of meters per hour.[153] Simply expressed, the drilling of a borehole can be performed significantly faster when drilling down-the-hole than when rotary drilling. Because of that advantage, down-the-hole drilling is often used when drilling through hard rock like granite and hard rock often is present when drilling deep geothermal boreholes. Hence, the number of down-the-hole drilling applications in deep

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[150] Refer to YouTube, https://www.youtube.com/watch?v=zO3gcJnA4-k (accessed: 19.04.2023)
[151] Source: Slide Share, https://www.slideshare.net/anilitbhu/down-the-hole-drilling-31393456 (accessed: 20.04.2023)
[152] Refer to Catalin, T. ;(2011), page 1
[153] Refer to Energy Glossary, https://glossary.slb.com/en/Terms/r/rate_of_penetration.aspx (accessed 20.04.2023)

geothermal drilling projects is recently growing. This is simply because a relatively high rate of penetration can be achieved, thus drilling can be conducted in a considerably shorter time than with conventional rotary drilling. However, there is also a downside when using the DTH method for deep wells. A disadvantageous example is the more frequent failure of downhole equipment because of being exposed to the intense vibrations produced by the hammer. Another disadvantageous example is the very high energy input required by this technique. To be able to circulate out the cuttings from wells several thousand meters in depth, sometimes almost 20 heavy-duty air compressors are required and this causes exorbitant costs. It is necessary to weigh up in advance of a deep drilling project, if it is more economical to cut down drilling time by using DTH or if it is disadvantageous because of high energy costs.[154]

The last alternative drilling method that is briefly described in this chapter, is the core drilling technique which is mainly used to drill exploration wells. An exploration well has a very small diameter (10 cm or even smaller), is not supposed to produce any medium, and has the purpose of investigating the subsurface conditions. To drill a production or injection well, so a well with a larger diameter, drilling with a coring rig is not feasible. Coring rigs are completely different from rotary rigs in the way they haul out the core. Typical core drilling rigs use a hollow drill bit and hollow drill pipes and bore a hole by rotating them. Coring rigs cut the core by the bit and store it in a tube at the lower end of the drill string as the hole advances. At certain intervals, a wireline is lowered down the inside of the drill string and is latched into the top of the core tube to get it to the surface. In that way, a continuous core over an interval of the hole can be obtained, which is very useful in the exploration of the subsurface. Because coring rigs do not require the application of drilling mud, it comes along with numerous equipment less than when drilling with a rotary rig. According to this fact, the drilling site is dimensioned relatively small, as Figure 43 shows. However, this technique can only be applied for very slim and rather shallow holes, hence mainly is performed for exploration purposes.[155]

[154] Refer to YouTube, https://www.youtube.com/watch?v=KP-0CjmEZng&t=30s (accessed: 20.04.2023)
[155] Refer to Finger, J.; Blankenship, D.; (2010), page 20 p.

Figure 43: Coring rig[156]

The reason why these alternative drilling machines and rigs are briefly introduced is that they are frequently and successfully applied in geothermal drilling projects. Therefore, the planned, converted workover rig is supposed to dispose of similar or even enlarged capabilities, in order to keep up with these machines.

[156] Source: Mining Connection, https://miningconnection.com/surface/news/article/boart_longyear_adds_new_rigs_to_meet_the_demand_of_expanding_exploration_bu/ (accessed: 18.04.2023)

2.5 Legal frame of geothermal utilization

How the development and the utilization of geothermal energy is legally regulated, is briefly introduced in this chapter. In the context of this thesis, it is sufficient to mention the relevant laws without presenting them in detail. As in previous chapters, the focus is on Austria and Germany.

2.5.1 Legal frame of geothermal utilization in Austria

In Austria, the subsurface beneath a property belongs to the owner of the property (§ 297 ABGB). Therefore, also the geothermal energy that resides in the subsurface belongs to the owner of the property. However, there are certain regulations when it comes to the development and utilization of it. Especially, the rights of a third party are not allowed to be affected by the development and utilization of geothermal energy. For instance, the utilization must be to an appropriate extent, so no ground heat is extracted from the adjacent property. Hence, approval by the authorities is required to utilize geothermal energy. The approval depends on the type of utilization.

When the production of geothermal energy includes the extraction of groundwater, the Austrian water law ("Wasserrechtsgesetz 1959") must be complied with. Concretely, this law states that extracted groundwater must be reinjected into the same aquifer after using it for energy purposes. Since, the reinjection impacts the temperature conditions of the aquifer, a license granted by a water law authority is necessary. If the extracted volume of groundwater exceeds 10 million m^3 respectively five million m^3 in specially designated areas, an assessment of environmental effects ("Umweltverträglichkeitsprüfung") is mandatory.

In case, the utilization requires the establishment of a well deeper than 300 meters, the Austrian mining law ("Mineralrohstoffgesetz") takes effect. This is stated in paragraph 119, section 1 of the Austrian mining law. Thus, a mining license granted by the Austrian mining authority ("Montanbehörde") is necessary to be allowed to drill.[157] The Austrian mining authority ("Montanbehörde") requires the following information in order to grant a license:

- A description of the planned well.
- Plans and calculations concerning the well.
- A list of the properties on which the well is planned and the names and addresses of the property owners.
- Information about the waste that is to be expected by the establishment and operation of the well. Information about precaution, prevention, and removal of that waste.

[157] Refer to 360° Erneuerbare Energie, https://www.360ee.at/energie-aus-der-tiefe-rechtliche-grundlagen-der-geothermie/ (accessed: 31.03.2023)

- Information about emissions that can be produced during the establishment and operation of the well.
- Presentation of an emergency plan in case of a serious accident that endangers the health of people and the well-being of the environment.[158]

Especially, the design of the well plays a crucial role in the approval process of the project by the Austrian mining authority (“Montanbehörde”). The casing and the cementation of the well must be designed in a way so that no communication between two underground geological horizons or communication with the surface is possible. Requirements regarding the casing and cementing design and the application of wellbore barriers (for example a BOP) are determined in the Austrian mining regulation (“Bergbauverordnung”).[159] In some cases, depending on the area, the drilling of a well deeper than 1 000 meters, additionally, requires an assessment of environmental effects. If the geothermal application is a closed system, thus, does not produce groundwater and its depth does not exceed 300 meters, usually, no license is required. In case an aquifer or a water reserve is located in the area, the water law authority must also grant closed geothermal systems.[160] Figure 44 summarizes the authorization process for geothermal projects in Austria.

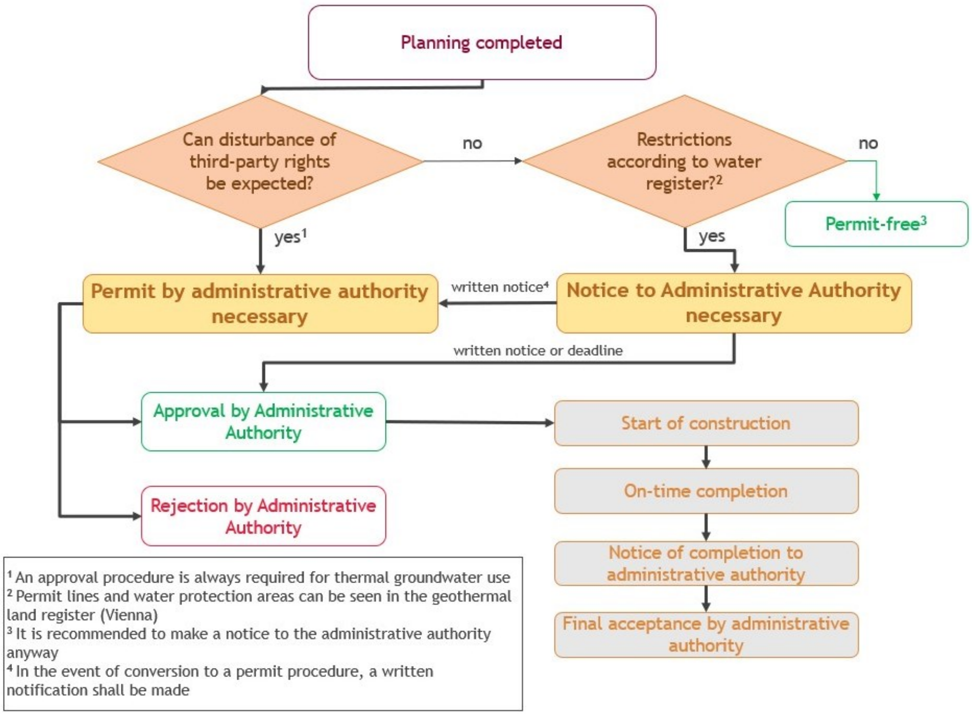

Figure 44: Authorization process of geothermal applications in Austria[161]

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[158] Refer to Rechtsinformationssystem des Bundes, https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=10008040 (accessed: 31.03.2023)

[159] Refer to Spörker, T.; (2023), personal communication

[160] Refer to 360° Erneuerbare Energie, https://www.360ee.at/energie-aus-der-tiefe-rechtliche-grundlagen-der-geothermie/ (accessed: 31.03.2023)

[161] Source: Erdwärme Wien, https://www.erdwaerme-wien.info/rechtliches/ (accessed 31.03.2023) (slightly modified)

Generally, in Austria, deep geothermal applications are only allowed to be drilled by a government-approved master for water well construction (“Brunnenmeister”) and/or by a master builder (“Baumeister”).

Besides different Austrian laws like the water law and the mining law, also numerous (inter-)national standards and norms need to be considered when planning, constructing, and operating a geothermal energy application. These standards are listed in Appendix A, because in the context of this thesis, it is sufficient to only list the most prominent ones, without further explaining them.

2.5.2 Legal frame of geothermal utilization in Germany

Opposite to Austria, geothermal energy is a so-called “bergfreier Rohstoff”, which means that it does not belong to the owner of the property under which it resides. To be allowed to use it, it requires a mining authority granted by the state´s administrative mining office (“Landesbergamt”). However, two geothermal applications are exempt from such a mining authority:

- Plants that already produced geothermal energy for bathing and healing purposes when the “Bundesberggesetz” came into effect.
- Noncommercial usage of geothermal energy on a particular property in connection with its structural use. An example is the use of a heat pump to heat a private house.

Independent of the necessity of a mining authority, every well that is supposed to be drilled deeper than 100 meters into the subsurface must be reported to the administrative mining office.[162] The office then examines if an operating plan (“Betriebsplan”) must be handed in. Normally, an operating plan is only requested when the planned well potentially poses risks for people and the environment. Such a plan must depict the extent, the technical procedure, and the duration of the project. Additionally, the plan should prove that the following criteria are fulfilled amongst others:

- Authority to explore and produce the resource.
- Prevention of hazards for life, health, and assets by safety measures and compliance with the law regarding safety at work.
- No disturbance of resources that are of public interest.
- Appropriate usage or removal of waste.
- Provide precautions for the reuse of the property after production.
- No negative impacts are to be expected for the community by drilling and production.[163]

[162] Refer to Energie Experten, https://www.energie-experten.org/erneuerbare-energien/erdwaerme/erdwaermebohrung/genehmigung (accessed: 03.04.2023)
[163] Refer to Bundesministerium der Justiz, http://www.gesetze-im-internet.de/bbergg/BJNR013100980.html#BJNR013100980BJNG000200315 (accessed: 03.04.2023)

In case, the geothermal usage is noncommercial, is performed on one´s property, does not impact the adjacent properties, and does not include wells deeper than 100 meters, the German mining law does not come into effect.

Besides the German mining law, also the German reservoir law ("Lagerstättengesetz") exists. According to this reservoir law, all drilling actions executed by machines and all geophysical explorations must be reported to the responsible administrative geology office. The report for drilling actions must include the plan of the site, the geological layout, and further exploration results. The report for geophysical exploration must include the plan of operation and the method and extent of the exploration.

Like in Austria, drilling actions in Germany must comply with German water law. Generally, according to the German water law ("Wasserhaushaltsgesetz") every person that performs geothermal drilling jobs or operates geothermal applications is responsible for not contaminating groundwater. Systems that produce from an aquifer require authority to do so. Closed systems that do not produce groundwater only need authorization on rare occasions. Independent of the type of the system, geothermal wells need to be reported to the local authorities. The report needs to be handed in before construction works commence and must include the plan of the site, the planned depth, and the configuration of the application. Especially, when more than one groundwater formation is drilled through, the authority initiates a water law procedure ("wasserrechtliches Verfahren"). Eventually, the drilling project can be approved or enjoined. In case, the well is drilled through numerous groundwater formations, it is determined by the German water law that the well must be completely cemented from its top to its bottom.

As in Austria, also in Germany specific areas are especially protected. These protected areas are defined in the water protection area ordinance ("Wasserschutzgebietsverordnung") and determine if a well must fulfill further requirements or is prohibited in any case.[164]

[164] Refer to Energie Experten, https://www.energie-experten.org/erneuerbare-energien/erdwaerme/erdwaermebohrung/genehmigung (accessed: 03.04.2023)

2.6 Procedures and instruments for the economic evaluation of conversion and feasibility

In this chapter, the instruments used for the economic evaluation of the conversion of a workover rig into a drilling rig are presented. Besides a theoretical introduction to these instruments, it is also explained why these instruments are used in this context and what explanatory power they have.

CAPEX

The first instrument that is applied in the practical part of this thesis is the cost calculation. After elaborating on the conversion process from a technical point of view, it is calculated what costs this conversion process generates. Therefore, the individual costs of the required equipment are listed and accumulated. This process is very straightforward and identifies the capital expenditures (CAPEX) on additional equipment required for the conversion of the rig. CAPEX is a very important economic term in the context of this thesis, so a brief definition is given: *Capital expenditures (CAPEX) are funds used by a company to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment.*[165] CAPEX, like in this case, often are used to undertake new projects or investments and, usually, only include items that have an operating life time of a minimum of one year. Since different types of assets can attribute long-term value to a company, several types of investments can be considered as CAPEX. Examples are investments into buildings, land, equipment (as in this case), computers, furniture, vehicles, and patents. The dimension of CAPEX varies among different industries. Industries like oil and gas exploration and production, telecommunications, manufacturing, and utility industries are capital-intensive industries and, hence, have the highest levels of capital expenditures.[166]

It is important to mention that in the course of this thesis, it is assumed that the entire CAPEX will be self-financed. This means that the calculations in the practical part do not take into account any financing costs due to the use of outside capital.

OPEX

The second cost calculation conducted in the practical part of this thesis deals with the operating expenses (OPEX) of the converted workover rig. Like CAPEX, OPEX is an important term in this thesis, thus, a definition is provided: *Operating expenses are the costs that a company incurs while performing its normal operational activities. Operational activities are those tasks that must be undertaken from day to day to operate*

[165] Investopedia, https://www.investopedia.com/terms/c/capitalexpenditure.asp (accessed: 28.08.2023)
[166] Refer to Investopedia, https://www.investopedia.com/terms/c/capitalexpenditure.asp (accessed: 04.07.2023)

the business and generate revenue.[167] Operating expenses can differ among companies and industries. Common examples of operating expenses are rent, sales and marketing fees, accounting and legal fees, payroll, insurance, repairs, and bank charges. OPEX can be distinguished into fixed or variable costs. A fixed cost is set for a predefined period of time, hence, does not change, while a variable cost can change, depending on the production and sales levels of products or services. Fixed costs, typically, relate to recurring expenses such as rent, interest payments, insurance payments, and bank fees. These costs are not affected by the production levels of goods and services. Variable costs increase or decrease depending on the production or sales rate, concretely, they rise as production increases and fall as production decreases.

In most companies and industries, OPEX are unavoidable, which is why it is all the more important to control them optimally. Reducing operating expenses can result in gaining a competitive advantage and increasing earnings. However, reducing operating expenses can also have negative impacts on the integrity and quality of operations. Thus, the management´s challenge is finding the right balance.[168]

To determine the OPEX for operating with the converted rig, a case study regarding a potential project for the converted workover rig is performed. The case study aims to calculate and record all kinds of costs that accrue when drilling with the converted workover rig. The case study, conducted to identify the OPEX, lists all cost drivers when drilling with the converted rig. Concretely, in the case study, five operative cost groups are identified and quantified. Table 1 shows an overview of these cost groups and additionally gives information on whether the cost group is fixed or variable.

Table 1: OPEX

<table>
<tr><th>Category</th><th>Type</th><td rowspan="5">Project-related OPEX</td><td rowspan="6">Total OPEX</td></tr>
<tr><td>Personnel costs</td><td>Variable costs</td></tr>
<tr><td>Equipment costs</td><td>Fixed costs</td></tr>
<tr><td>Material costs</td><td>Variable costs</td></tr>
<tr><td>Miscellaneous costs</td><td>Variable costs</td></tr>
<tr><td>Overhead costs</td><td>Variable costs</td><td></td></tr>
</table>

The personnel costs, equipment costs, material costs and miscellaneous costs are project-related OPEX, since they can be accounted directly to a certain project. Personnel costs result from fixed hourly wages and variable allowances. Because allowances, hours worked, as well as the number of workers can vary between different projects, personnel costs are categorized as variable. Since the equipment costs include

[167] Investopedia, https://www.investopedia.com/terms/o/operating_expense.asp (accessed: 28.08.2023)
[168] Refer to Investopedia, https://www.investopedia.com/terms/o/operating_expense.asp (accessed: 04.07.2023)

repairs and maintenance and these occur at irregular intervals, this cost group should actually be fixed. In this case, however, a predefined flat rate is assumed for repairs and maintenance which results from empirical values. Furthermore, this cost group includes imputed costs, that also are predefined. Therefore, this cost group is a fixed one. Material costs and miscellaneous costs (include energy consumption and logistics) can vary between projects, so these cost groups are variable.

The last operative cost group depicted in Table 1 are the overhead costs, which cannot be directly assigned to a single project but are divided aliquot between the different projects. These overhead costs cover, for example, costs such as office building rent, office staff personnel costs, and marketing and sales costs. In this case, the overhead costs are calculated as a fixed percentage of the project-related OPEX. Since project-related OPEX can vary, the overhead costs can also differ among projects. Therefore, overhead costs can be regarded as variable.[169]

Key performance indicators

One of many possible definitions of key performance indicators (KPIs) is the following: *A Key Performance Indicator (KPI) is a type of measure that is used to evaluate the performance of an organization against its strategic objectives. KPIs help to cut the complexity associated with performance tracking by reducing a large amount of measures into a practical number of 'key' indicators.*[170]

In other words, key performance indicators are a set of quantifiable measurements, which assess a company's performance against targets and goals. KPIs are an important management tool for gaining insight and decision-making. In the context of this thesis, KPIs are supposed to assist in making a strategic decision, namely, if the conversion of the workover rig is economically feasible or not. Generally, different categories of KPIs exist. Examples are KPIs regarding timeliness, finances, quality, and effectiveness. In the course of the practical part of this thesis, only financial KPIs are covered. Table 2 lists which KPIs are actually calculated in the practical part.[171]

[169] Refer to Schellenberg, D.; (2023), personal communication
[170] SimpleKPI, https://www.simplekpi.com/Resources/Key-Performance-Indicators (accessed: 28.08.2023)
[171] Refer to Investopedia, https://www.investopedia.com/terms/k/kpi.asp (accessed: 04.07.2023)

Table 2: Selected KPIs

KPI
CAPEX
OPEX
Project´s net sales price
Revenue
Gross profit
Gross profit margin
Earnings before interests and taxes (EBIT)
Earnings before interest, taxes, depreciation, and amortization (EBITDA)
Net profit
Cash flow
Return on investment
Payback period
Price per meter drilled

Sensitivity analysis

In the course of the practical part, the CAPEX and the OPEX are calculated. In order to analyze their composition, the economic tool of sensitivity analysis is applied. Theoretically, a sensitivity analysis studies how various sources of uncertainty in a mathematical model contribute to the overall uncertainty of the model. In other words, a sensitivity analysis determines how different values of an independent variable affect a particular parameter. Therefore, this type of analysis is also referred to as a what-if or simulation analysis. A sensitivity analysis can be a very useful tool for management as it assists in understanding influencing factors, reducing uncertainties, achieving goals, and catching errors.[172]

In the practical part, the conducted sensitivity analysis investigates how the total costs change, when single cost drivers change. Concretely, the influence of the individual costs on the total costs is shown graphically. This procedure is done for the CAPEX as well as for the OPEX. Thereby, it is highlighted which cost drivers have the most impact on the CAPEX respectively the OPEX. The information that can be gained from the sensitivity analysis can be used to identify which costs require special attention and which costs are supposed to be reduced in order to achieve the greatest effect.

[172] Refer to Investopedia, https://www.investopedia.com/terms/s/sensitivityanalysis.asp (accessed: 05.07.2023)

Market analysis

The instrument that is applied in Chapter 3.6 of the practical part, is the market analysis. A market analysis is a detailed assessment of a target market and its competitive landscape within a specific industry. Conducting a market analysis should enable a company to do the following:

- Detection of trends and opportunities in a certain industry.
- Differentiation of the competitors.
- Risk and cost reduction when launching a new product or service.
- Tailoring of products and services to the target customers' needs.

Figure 45 presents a possible procedure for a market analysis.

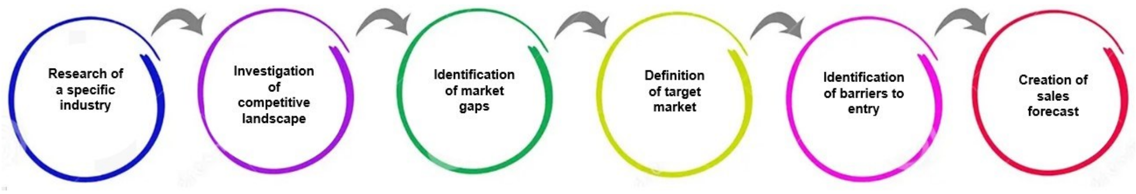

Figure 45: Market analysis method[173]

The steps presented in Figure 45 are the following:

1. Research of a specific industry: The purpose of this step is to gain an understanding of the industry at large. It is learned how the industry could be entered, trends are spotted, and the competition is understood.
2. Investigation of the competitive landscape: The competitor's range of services and products is investigated.
3. Identification of market gaps: With insights into how the competition operates, market gaps can be identified. Market gaps are needs that are currently not filled by operating companies.
4. Definition of target market: By knowing the industry, the competition, and the market gaps, the target market can be defined. This includes the identification of potential customers and the differentiation of planned products and services to stand out within the industry.
5. Identification of barriers to entry: After defining the target market and tailoring services and products, it is important to have a clear sense of factors that might be problematic when entering the market and operating within it.
6. Creation of sales forecast: Sales forecasting is the process of estimating future sales so that confident business decisions can be made.[174]

[173] Source: Coursera Inc., https://www.coursera.org/articles/market-analysis (accessed: 30.05.2023) (modified)
[174] Refer to Coursera Inc., https://www.coursera.org/articles/market-analysis (accessed: 30.05.2023)

These steps are presented to give an idea of how a market analysis can be composed. The market analysis conducted in this thesis does not strictly proceed according to this schematic. Its focus is on generating an understanding of the drilling industry in Austria and Germany. It is elaborated on which players operate in the industry and what kind of services and products they offer. Subsequently, it is investigated, if there is a potential market for drilling with converted workover rig. Hence, the first four of the six working steps listed above are conducted in the practical part of this thesis.

3 Practical part

The practical part is all about the changeover process of a workover rig into a drillable rig. On the basis of a particular type of workover rig, namely the Confind AM12/50, it is identified which additional elements are required and why these are required. Subsequently, the costs (CAPEX) that generate in the course of the changeover are calculated. After determining the CAPEX, it is investigated what the realization of drilling projects with the converted rig costs (OPEX). This is necessary to know at what price the services of the concerted rig can be offered and if this is competitive. In order to be able to check the competitiveness, KPIs are calculated and a market analysis is carried out. In addition, the practical part includes a sensitivity analysis to identify potential savings in the CAPEX and the OPEX and a Gedankenexperiment dealing with sustainable drilling.

3.1 Conversion of a workover rig into a drilling rig

In this chapter, workover and the therefore used workover rigs are introduced. Subsequently, the differences between workover and drilling rigs are worked out. Eventually, the changeover of a workover rig into a drilling rig is discussed on a technical and financial basis.

3.1.1 Introduction to workover and workover rigs

At a certain point in the producing life of an oil and gas well, the initial well conditions change, and the production rate declines, even though the reservoir still contains considerable amounts of hydrocarbons. The reason why the production rate declines over time, is that the reservoir pressure is continuously decreasing. This is when well workover comes into play.[175]

Well workover is an integral part of the oil and gas industry and includes all techniques with the purpose to restore, prolong, or enhance the production of hydrocarbons by invading an existing production well. Examples of situations that require well workover are the following:

- Production tubing, downhole pumps or other downhole equipment are damaged or malfunction due to operational factors.
- Occurrence of corrosion to the point where well integrity is at risk.
- New completion elements are needed due to declined reservoir conditions.
- The well is to be abandoned, hence needs to be filled with cement.[176]

[175] Refer to Slide Share, https://www.slideshare.net/ChristianAkhilome/well-workover-54426045 (accessed: 05.04.2023)
[176] Refer to Guo, B. et al.; (2017), page 503

Workover jobs can be distinguished between heavy workover jobs and light workover jobs. According to the type of workover job, either a heavy workover rig or a light workover rig is required for the execution. Generally, heavy workover jobs are more extensive and complex than light workover jobs. However, the characterization of the workover job also depends on the affected depth. Thus, even relatively straightforward workover tasks require a heavy workover rig at depths of a few thousand meters. Examples of heavy workover jobs are the abandonment of a well or the milling of downhole equipment.[177] An example of a light workover is the replacement of a downhole pump.[178]

Heavy and light workover rigs are conventional workover rigs and are similarly constructed to drilling rigs but of smaller dimensions. Therefore, they include a mast, a hoisting system, and a power system. Systems that most light workover rigs are lacking are the rotary system, the circulating system, the solid control system, and the well control system. This is because the majority of light workover jobs do not include drilling but are conducted on cased and cemented wells. Thus, the rotation of a drill string, the circulation of drilling mud, the separation of crushed material from the drilling mud, and the prevention of a kick respectively a blowout are all not required. In practice, light workovers often include the removal of hundreds or even a few thousand meters of tubing. Thus, the heart of a light workover rig is its hoisting system. Heavy workover rigs differ from light workover rigs, because they have much higher hook load capacities, hence can manipulate longer and heavier tubing strings. Additionally, many heavy workover rigs are equipped with a rotary system, so they can mill out downhole equipment or drill side-tracks at existing wells. When drilling side-tracks, the heavy workover rigs also need to be outfitted with smaller versions of circulating, well control, and solid control systems.[179] Many workover jobs require the killing of the well in advance. Killing the well means circulating fluid into the well whose density is high enough to generate a hydrostatic pressure that can hold back formation fluids. In other words, this so-called killing fluid stops the production of oil and gas. This circulation of killing fluid can be conducted by an external pump truck, in case the workover rig is not equipped with a circulating system.[180] At this point, it should be mentioned that there are also minor workover jobs, that do not require the killing of the well and the pulling of the production tubing. In these cases, no workover rig is needed but smaller units enter the well through the production tubing with, for instance, a wireline.[181] However, in the context of this thesis, conventional workover rigs are of interest. A conventional workover rig can easily be moved since it is mounted on a truck. Hydraulic cylinders erect the mast, hence workover units are a subcategory of the “Push-type” masts. One needs to distinguish between back-in ramblers (BIR) and drive-in ramblers (DIR). DIR trucks

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177 Refer to MB Well Services GmbH, https://www.mbwellservices.com/en/service/drilling-heavy-workover/ (accessed. 23.05.2023)
178 Refer to MB Well Services GmbH, https://www.mbwellservices.com/en/service/light-workover-en/ (accessed. 23.05.2023)
179 Refer to MB Well Services, https://www.mbwellservices.com/service/anlagen/ (accessed: 23.05.2023)
180 Refer to Slide Share, https://www.slideshare.net/ChristianAkhilome/well-workover-54426045 (05.04.2023)
181 Refer to Guo, B. et al.; (2017), page 504 p.

approach the wellbore forwards and BIR trucks with their rear parts. Figure 46 shows an impression of the BIR type, which is the more common type nowadays.[182]

Figure 46: BIR type workover rig[183]

The passage above indicated that various types of workover rigs exist. Workover rigs can vary in their integrated systems, their hook load capacities, their mobility, their fields of application, and many more characteristics. Therefore, the changeover of a workover rig into a drilling rig can only be discussed on the basis of a specific type of workover unit. In this case, the target for the changeover is the AM12/50 workover rig. This type is a light workover unit of the BIR type, manufactured by the Romanian company Confind S.R.L.. Since mounted on a heavy-duty truck, it is mobile and at the site, it is capable of fully erecting to its working position using integrated hydraulic cylinders. In the next chapter, it is explained what needs to be done, to make the AM12/50 drillable.

3.1.2 Changeover of the Confind AM12/50

The rig´s manufacturer lists the following tasks as possible fields of application for the AM12/50:

- Tubing running in/pulling out
- Sucker-rod running in/pulling out
- Replacement of downhole pumps
- Instrumentation at the rig site
- Bailing and swabbing jobs

[182] Refer to Wirth, S.; (2022)
[183] Source: SIS Auto, https://sisuauto.com/wp-content/uploads/IMG_5131.jpg (accessed: 24.11.2022)

- Casing out-of-roundness removals
- Well columns repairs
- Fishing jobs and tests while in production

Without further explaining these tasks, it can be stated that they all just require the hoisting function of the rig. Hence, the AM12/50 comprises a mast, a hoisting system, and a power system that supplies the drawworks. In the course of this chapter, it is explained which further systems and equipment the AM12/50 requires to be able to drill. At this point, it needs to be declared that the presented changeover process concentrates on the required key elements. In case, such a changeover process is undertaken, many complex engineering factors need to be considered, to effectively attach additional systems to an existing rig. Before discussing the changeover, the features of the AM12/50 are briefly introduced. Table 3 lists the characteristics of the AM12/50. Hook load, power, clear height, and height of the rig floor are crucial for the changeover. The reasons why these are key features are presented in the course of this chapter.

Table 3: Key characteristics of AM12/50 workover rig[184]

Characteristic	Quantity
Maximum hook load	50t
Maximum power	375 HP (280 kW)
Total weight when completely assembled	36.500 kg
Maximum clear height	21m
Maximum height of rig floor	3m
Rig working temperatures	-20°C to 40°C

To get an idea of the AM12/50´s composition and its measurements, Figure 47 and Figure 48 present diagrams of it.

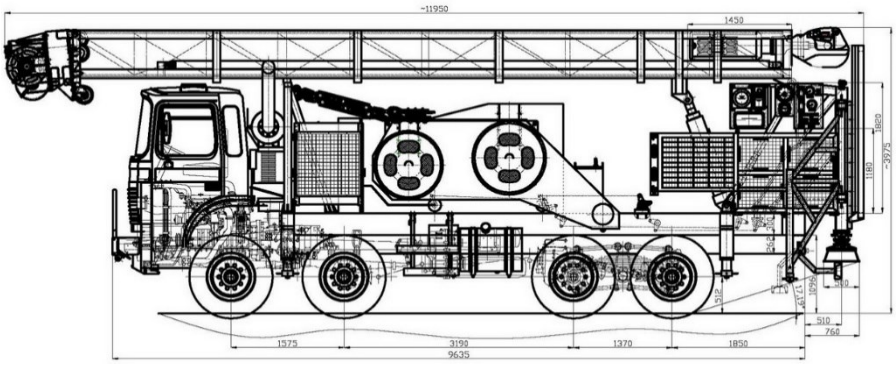

Figure 47: AM12/50 with retracted mast[185]

[184] Refer to Confind S.R.L.(w.rd.), page 5 pp.
[185] Source: Confind S.R.L.(w.rd.), page 16 pp.

Figure 47 shows the rig in its transport position with a retracted mast. In this position, it has a height of nearly four meters, a width of 2,5 meters, and a length of nearly 12 meters. The maximum driving speed of the AM12/50 is 50 km/h. This is problematic because the minimum running speed on German highways is 60 km/h.[186] In Austria, the minimum running speed on highways is also 60 km/h.[187]

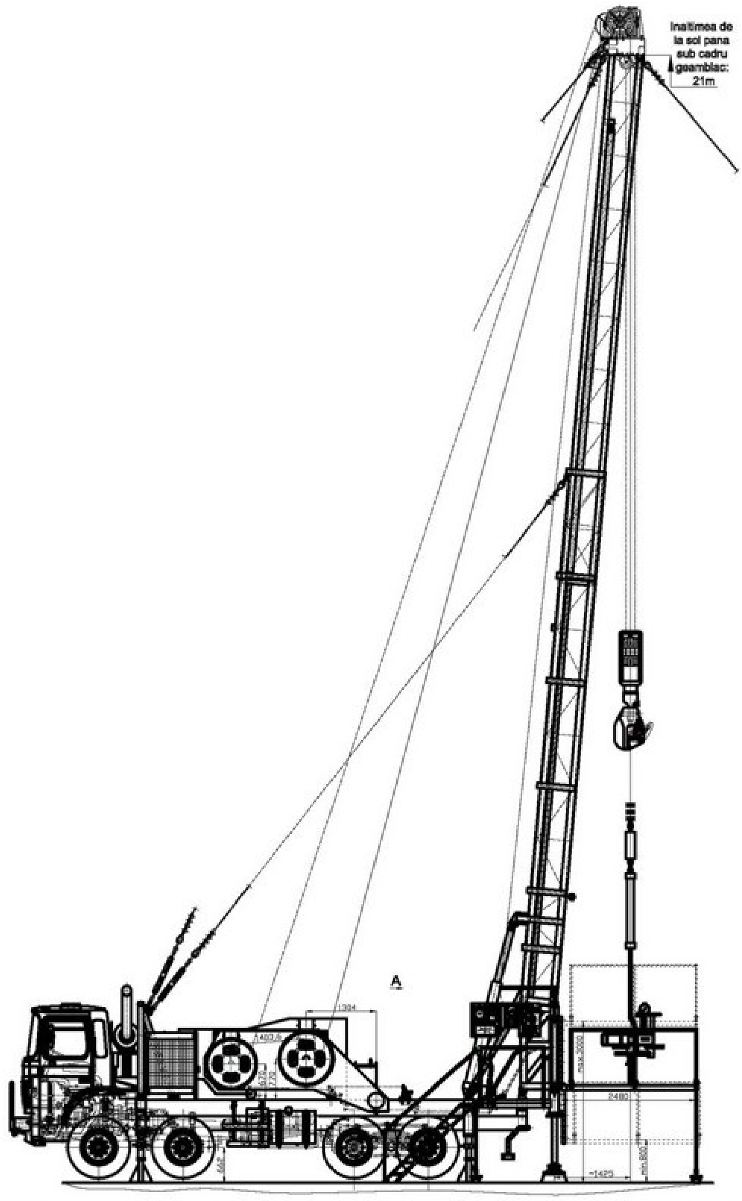

Figure 48: AM12/50 in its working position[188]

Figure 48 presents the AM12/50 in its working position with an erected mast. In that position it has a length of 14,43 meters and its mast has a clear height of 21 meters. Certainly, the clear height depends on the height of the rig floor, which is adjustable

[186] Refer to Confind S.R.L.(w.rd.), page 5 pp.
[187] Refer to ADAC, https://www.adac.de/verkehr/recht/verkehrsvorschriften-deutschland/mindestgeschwindigkeit/ (accessed: 25.05.2023)
[188] Source: Confind S.R.L.(w.rd.), page 15 pp.

between 0,8 and three meters. When the rig floor, for instance, is set at its maximum height of three meters above the ground, a clear height of 18 meters remains.[189]

To be able to theoretically convert the AM12/50 into a drillable rig, several assumptions need to be made. In practice, drilling rigs are selected and equipped according to the characteristics of the drilling project. Concretely, the well objectives are determined to understand what the rig needs to be capable of. Examples of well objectives are the well depth, the well diameter, or the casing design. Therefore, it is necessary to define a potential project with certain well objectives, that are supposed to be realized by the converted AM12/50. The following realistic well objectives are defined for this purpose.

The well is to be drilled vertically and has a total depth of 700 meters. This depth is referred to in the drilling industry as medium-deep. Due to the hook load of the AM12/50 (50 tons), which is the limiting factor in this case, it can be ruled out that the rig is able to drill deeper than 700-800 meters. This is a very crucial realization as it determines that the converted rig is supposed to be applied in the medium-deep drilling sector.

The casing that is to be installed inside the borehole is supposed to have an outer diameter of 9 5/8 inches (24,45 cm). Projects, where oil and gas wells are changed over into geothermal wells, acted as a reference for choosing this casing size. Casings are available with different wall thicknesses, thus, have different weights. For this purpose, a casing with a rather small wall thickness and a weight of 36 pounds per foot (53,11 kilogram per meter) is sufficient. The setting of the casing presents the highest load that needs to be supported by the rig. When assuming that the casing needs to be set to a total depth of 700 meters, the weight of the casing string accumulates to 37.2 tons. At the stage when the casing is set, the borehole is filled with drilling fluid, so that the effective weight of the casing string is reduced due to buoyancy. However, in practice, the weight of the casing string is calculated in air, so a safety factor is included when reconciling the casing string´s weight with the bearable hook load of the rig. Since the AM12/50 can bear a maximum hook load of 50 tons, it is capable of setting the selected casing to a depth of 700 meters. Nevertheless, it is also necessary to install a conductor and this cannot be performed by the AM12/50.[190] The conductor is a short but large-diameter pipe that is set to support the surface formations. Typically, the conductor is installed soon after drilling has been initiated since the unconsolidated shallow formations can quickly wash out or cave in. At some locations, where loose surface soil exists, the conductor is driven into place before drilling starts.[191] Figure 49 presents a typical casing design for a deep well, including a conductor, a surface casing, an intermediate casing, and a production casing. For a medium-deep well, the installation of a conductor and a surface casing is sufficient. As already mentioned, the surface casing of the designed well has an outside diameter of 9 5/8 inches. The conductor, in this case, is supposed to be around 25 meters long and 13 3/8 inches (33,97 cm) wide.

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[189] Refer to Confind S.R.L.(w.rd.), page 5 pp.
[190] Refer to Eibl, J.; (2023), personal communication
[191] Refer to Schlumberger Energy Glossary, https://glossary.slb.com/en/terms/c/conductor_pipe (accessed: 28.06.2023)

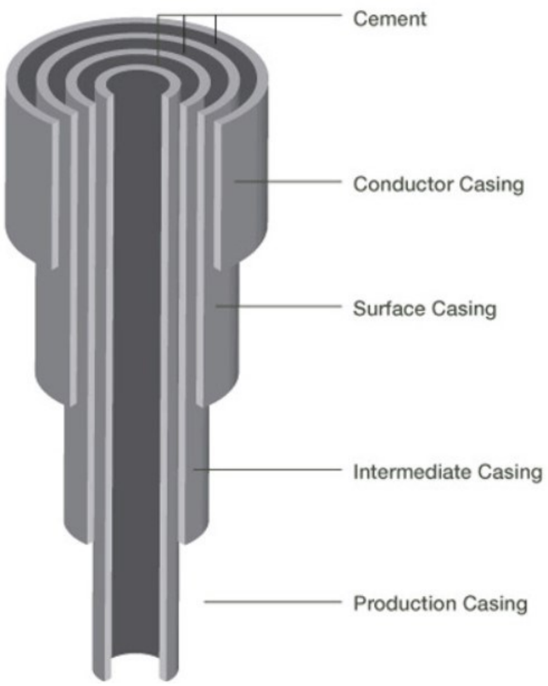

Figure 49: Casing design[192]

The limiting factor, for which reason the AM12/50 cannot install the conductor, is the rotary table. The AM12/50 is not designed for a rotary table that is large enough, so a conductor of this size can pass through. Thus, it can be anticipated that the setting of a conductor needs to be conducted by another machinery than the AM12/50.

After determining the essential well objectives, it can be defined with which additional equipment the AM12/50 needs to be fitted in order to realize the outlined well. In the following passage, the necessary equipment is listed and further explanations and considerations are provided.

- Rotary head: This tool serves as a rotary source for the drill string. Key features of a rotary head are its maximum rotational speed (unit is RPM- revolutions per minute) and its maximum torque (unit is Nm- Newton meter). To meet the requirements of the outlined well, the rotary head needs to be capable of delivering rotational speeds of around 40 RPM and torques of around 9 kNm. This performance can be conducted by a rather small, low-duty, and hydraulically driven rotary head. Typically, such rotary heads are smaller than one meter in length. So, it can be assumed that the combination of traveling block, hook, and rotary head reduces the mast´s clear height by approximately 2,5 to three meters. Additionally, the rotary head needs to be compatible with the size of the drill pipes.[193]
- Power unit for the rotary head: The rig´s diesel engines have a power of 375 HP (280 kW). Since the rig is primarily designed to hoist, 90% of that power is consumed

[192] Source: Business Gateways, https://businessgateways.com/images/Products_cover/142907479829400.gif (accessed: 28.06.2023)
[193] Refer to Eibl, J.; (2023), personal communication

by the hoisting system, hence, the drawworks.[194] Therefore, most equipment that is added to the rig in the course of the changeover process needs to be driven by external power units. For the rotary head, in this case hydraulically driven, a hydraulic power unit with a capacity of around 50 kW is required.[195]

- Rotary table: The rotation of the drill string is powered by the rotary head. Nevertheless, a rotary table is required to support the weight of the drill string when it is detached from the hook, respectively the rotary head. In this case, the power of the rotary table is trivial when selecting an adequate type. The decisive parameter is the size of the rotary table, which needs to be big enough, so the casing can pass through.
- Drill bit: The size of the drill bit, which determines the borehole´s diameter is 12 1/4 inches (31,12 cm). This borehole diameter is required to be able to install a 9 5/8 casing. Different types of drill bits exist. For this purpose, a roller cone, a rather simple type, is sufficient.[196]
- Drill pipes: To drill a borehole of 700 meters deep and 12 1/4 inches wide, a drill pipe string of 650 meters in length is needed. The string consists of single pipes of 5 inch diameter.[197] Typically, a drill pipe is 31 feet (9,45 meters) long but the length can be customized, hence, can be anywhere from 18 feet (5,49 meters) to 45 feet (13,72 meters).[198] The length of the pipes should be chosen in a way so that the clear height of the mast can be utilized as well as possible. Assuming the clear height to be 17 meters, the recommended pipe length is around 8,5 meters. That way, two pipes can be manipulated at once and the adding and the removal of pipes can be accelerated.
- Drill collars: The drill string of 700 meters in length is completed by 50 meters of drill collars. Drill collars are thick wall and, therefore, heavy pipes that increase the weight on the drill bit, so it can efficiently break the rock.[199] The drill collar string consists of 31 feet (9,45 meters) long single drill collar pipes that are joint together and placed directly above the drill bit.[200]
- Mud pump: The decisive factor for selecting an adequate mud pump is the pump´s power. To calculate the required pump power for the outlined well, the following formula is applied.

$$P\,[\mathrm{W}] = \frac{\rho\left[\frac{\mathrm{kg}}{m^3}\right] * g\left[\frac{\mathrm{m}}{s^2}\right] * Q\left[\frac{m^3}{\mathrm{s}}\right] * h[\mathrm{m}]}{\eta\,[-]}$$

[194] Refer to Confind S.R.L.(w.rd.), page 5
[195] Refer to Wirth, S.; (2023), personal communication
[196] Refer to Eibl, J.; (2023), personal communication
[197] Refer to Wirth, S.; (2023), personal communication
[198] Refer to GlobalSpec, https://www.globalspec.com/learnmore/specialized_industrial_products/mining_equipment/drill_pipe (accessed: 28.06.2023)
[199] Refer to Schlumberger Energy Glossary, https://glossary.slb.com/en/terms/d/drill_collar (accessed: 29.06.2023)
[200] Refer to Bergmann, T.; (2023), Email

Whereas "P" stands for pump power, "ρ" stands for the density of the drilling mud, "g" stands for gravitational acceleration, "Q" stands for the flow rate, "h" stands for the height over which the fluid needs to be pumped, thus represents the borehole depth, and "Ƞ" stands for the pumps efficiency factor.[201] In the case of the outlined well, it is possible to utilize water as drilling mud, since its density is sufficient. The selected flow rate originates from the drilling data of an actual drilling job of the same depth.[202] The pump´s efficiency factor comprises an electrical, an mechanical, and a volumetric factor and can be assumed to be 0,77 on average.[203] When inserting the actual values, the formula produces the following result.

$$\mathrm{P}\ [\mathrm{W}] = \frac{1000\left[\frac{\mathrm{kg}}{m^3}\right] * 9{,}81\left[\frac{\mathrm{m}}{s^2}\right] * 0{,}05\left[\frac{m^3}{\mathrm{s}}\right] * 700\ [\mathrm{m}]}{0{,}77\ [-]} = 445.909\ [W]$$

Thus, to be able to circulate water through the borehole, a pump with the power of 445.909 W (598 HP) is required.

- Mud tanks: Tanks are needed to store, transport, and circulate the mud, or in this case the water. In practice, a very simple rule of thumb is applied for calculating the appropriate tank volume respectively mud volume. The tank, or the tanks, should dispose of a volume that is two times the borehole´s volume. The volume of the designed borehole is computed as follows.

$$V[m^3] = r^2[m] * \pi[-] * h[m] = 0{,}156^2[m^2] * 3{,}142[-] * 700[m] = 53{,}23\ [m^3]$$

Whereas "V" stands for the borehole volume, "r" stands for the borehole radius, "π" symbolizes the circle constant, and "h" stands for the depth of the borehole. Since the tanks are supposed to store twice the volume of the borehole, their volume is required to be 106,46 m^3. Because tanks only are available in certain size intervals, two 50 m^3 tanks are appropriate for this purpose.[204]

- Shale shaker: Regarding the dimension and complexity of the outlined well, the utilization of a shale shaker as the only solid control system is sufficient.
- Diesel generator sets: A diesel generator set is needed to run the shale shaker. Since a standard shale shaker has a motor power of around 5 kW, the diesel generator set is supposed to deliver power of such quantity. A second diesel generator set is required to cover miscellaneous energy needs, like powering the team container and the sanitary container.[205]

[201] Refer to Debem Deutschland GmbH, https://www.debem.com/de/leistung-einer-pumpe/ (accessed: 29.06.2023)
[202] Refer to Eibl, J.; (2023), Email
[203] Refer to Debem Deutschland GmbH, https://www.debem.com/de/leistung-einer-pumpe/ (accessed: 29.06.2023)
[204] Refer to Eibl, J.; (2023), personal communication
[205] Westpetro, https://www.west-petro.com/product/shale-shaker.html (accessed: 29.06.2023)

- Blowout preventer: As well control equipment, a BOP is applied. Regarding the dimension of the borehole and the minor risk of encountering overpressure formations or hydrocarbon reservoirs, a rather small and low-duty BOP with a working pressure of around 100 bar is sufficient. This BOP is supposed to be operated manually, so no accumulator unit is required. Since the purpose of drilling is not the development of oil and gas reservoirs but the establishment of a geothermal well, the application of a BOP as only well control equipment is adequate. In this case, a kick is not circulated through the choke manifold but transferred away from the well and released under controlled conditions. To be able to install the BOP on the conductor casing, a flange, and a spool are needed. Additionally, a valve needs to be installed below the BOP, through which the kick can exit the well.[206]
- Power tongs: To be able to screw the single pipes together, two power tongs are of need. One power tong rotates and the other one counters. Power tongs need to be aligned with the pipe´s diameter. For this reason, the power tongs can be fitted with inserts of various sizes. In this case, inserts for the drill pipes, the drill collars, and the casing pipes are required.[207]
- Master bushing: The master bushing is inserted into the rotary table and enables the suspension and support of the drill string. The size of the inner part of the master bushing, the tapered bowl, needs to be coordinated with the diameter of the pipe that is to be suspended. Therefore, three different sizes of tapered bowls are required for the drill pipes, the drill collars, and the casing pipes.[208]
- Slips: Between the master bushing and the pipe string, slips are placed when suspending the pipe strings. Similar to the master bushing, the slips need to be coordinated with the casing size, the drill pipe size, and the drill collar size.[209]

3.1.3 Cost calculation of the changeover process

After listing the different equipment and explaining the reasons for its necessity, the according costs and the accumulated CAPEX are presented in this chapter. It is vital to say, that only equipment is listed that needs to be bought in addition by CMB Well Services S.R.L.. The remaining equipment which is required for drilling (for instance the rig itself and many smaller items and tools that are required for workover jobs) are already owned by the company. Some of the listed equipment, for instance, the rotary head or the diverter system are complex equipment that, normally, is individually manufactured, thus varies in its costs. Furthermore, there are discrepancies in the purchase costs of equipment among different producers. Nevertheless, the CAPEX and the expected operating lives presented in Table 4 claim to be realistic guide values.

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206 Refer to Wirth, S.; (2023), personal communication
207 Refer to Weatherford, https://www.weatherford.com/products-and-services/well-construction-and-completions/tubular-running-services/traditional-systems/conventional/power-tongs/ (accessed: 03.07.2023)
208 Refer to Davis, L.D.; (2012), page 27-62
209 Refer to Wirth, S.; (2023), personal communication

Table 4: Cost of additional equipment

Equipment	**Costs of purchase**	**Operating life time**
Rotary Head	47.500€	15-20 years[210]
Power unit for rotary head	11.000€	15 years[211]
Rotary table	160.000€	15 years[212]
Drill bits	16.200€	1 year[213]
Drill pipes	64.675€	3 years
Drill collars	31.314€	3 years
Mud pump	800.000€	25-30 years
Mud tanks	125.000€	25-30 years
Shale shaker	150.000€	25-30 years[214]
2x Diesel generator set	4.000€	10 years[215]
BOP, spool, and flange	40.000€	15-20 years[216]
2x Power tongs	70.000€	10 years[217]
3x master bushings	11.000€	15-20 years[218]
3x Slips	1.800€	10 years[219]
Total equipment	**1.532.489€**	

The total additional investment accumulates to 1.532.489€. This sum generates when all the additional equipment is purchased as newly produced products. However, in the drilling sector, it is common practice to acquire relatively long-lasting equipment secondhand. Of course, these used elements should not have any qualitative

[210] Refer to Bergmann, T.; (2023), Email
[211] Refer to Ottersbach, S.; (2023), Email
[212] Refer to Bergmann, T.; (2023), Email
[213] Refer to Made in China, https://yinhaibits.en.made-in-china.com/product/VmBYcxCUHpWs/China-12-1-4-Tricone-Bit-311mm-Roller-Cone-Bit-Rock-Drill-Bit-for-Well-Drilling-API-Factory-Price.html (accessed: 30.06.2023)
[214] Refer to Bergmann, T.; (2023), Email
[215] Refer to Expondo, https://www.expondo.at/msw-notstromaggregat-diesel-5100-6000-w-16-l-240-400-v-mobil-avr-euro-5-10062300?msclkid=ccf0738ccf821baa666c1712481dd1a3&utm_source=bing&utm_medium=cpc&utm_campaign=%5BAT%5D%20%7C%20%5BPLA%5D%20%7C%20Shopping%20%7C%20Alle%20Produkte&utm_term=4586131723805267&utm_content=Alle%20Produkte (accessed: 30.06.2023)
[216] Refer to Wirth, S.; (2023), personal communication
[217] Refer to Bergmann, T.; (2023), Email
[218] Refer to Made in China, https://zjboral.en.made-in-china.com/product/zydJqMNvPXVe/China-Mpch-Master-Bushing-Made-in-China.html (accessed: 30.06.2023)
[219] Refer to Made in China, https://sdbeyondpetro.en.made-in-china.com/product/edhGKbqOKsVS/China-Drilling-Wellhead-Tools-Sdxl-Sdml-MP-Safety-Clamp-Drill-Collar-Slips-Dill-Pipe-Slip.html (accessed: 30.06.2023)

disadvantages compared to new elements, so that no higher operating costs arise by their application. For example, a rotary table that has been operating for seven years, can be bought for around 35.000€.[220] Thus, the sum of investment can be reduced significantly when buying certain equipment secondhand. However, in the course of this thesis, it is assumed that all of the equipment is purchased brand-new.

When regarding the composition of the total costs, it is of interest to set the single costs in relation to the according operating life time. It is noticeable that the most expensive equipment has relatively long operating life times. In numbers, 1.344.500€ (that is 87,7% of the total investment) is allotted to the purchase of equipment that lasts a minimum of 15 years. 1.075.000€ (or 70,1% of the total investment) is allotted to the purchase of equipment that even lasts a minimum of 25 years. The equipment with the shortest operating life times are the drill pipes, drill collars, and, especially, the drill bit, thus the components of the drill string. The operating life time of these components is not declared in years but in drilled meters. How many meters can be drilled with certain pipes, collars, and bits, depends on various factors like geology, weight on bit, or rotating speed. The operating life times presented in Table 4, therefore are just realistic guide values.[221] According to the indicated operating life times, every year 16.200€ need to be spent on drill bits, while every five years 95.989€ need to be spent on new drill pipes and collars.

It is also of interest to compare the CAPEX for the conversion process with the original cost of the workover rig. This cost accumulates to 1.350.000€ and the operating life time of the rig is expected to be between 25 and 30 years. Therefore, it can be stated that the conversion amounts to 113,5% of the original rig´s purchase cost which means that the CAPEX can be expected to double.

[220] Refer to Bergmann, T.; (2023), Email
[221] Refer to Drilling Manual, https://www.drillingmanual.com/drill-pipe-inspection-standards/?expand_article=1 (accessed: 03.07.2023)

3.2 Case study about the operation with the converted workover rig

After calculating the costs for the conversion process, this chapter deals with the costs that accrue when operating with the rig. To be able to identify the operating costs (OPEX), a case study is performed. The OPEX are supplemented by imputed costs and surcharges, thus at the end, the total costs for the client are presented. The case study is supposed to reflect the project costs concerning the establishment of the previously outlined well.[222]

To define frame conditions for the project reflected in the case study, various assumptions need to be made. These assumptions are listed in the following passage.

- The well that is to be drilled in the course of the case study is the previously outlined well. This well is fitted with casings and cemented over its total depth of 700 meters. The probe that is installed within the well also runs to the well´s total depth of 700 meters. It has already been mentioned that the converted AM12/50 is not capable of setting the conductor. Therefore, the task of setting the conductor is not incorporated into this case study. In practice, this task needs to be subtracted, hence, generating additional costs for the client.
- Besides defining the well´s characteristics, it is also necessary to define the location of the well. For this reason, it is assumed that the well is located in an urban area, 250 kilometers away from the company´s location where the drilling crew and the machinery are based. Making these geographic assumptions is necessary to compute the logistical costs. Additionally, the location of the well influences the operating hours of the rig and the crew. Since, assuming that the project is executed in an urban area, drilling is only performed during the daytime and only from Monday to Saturday.
- Due to the above-described circumstances, it is acted on the assumption that the drilling crew only works in day shifts, lasting 12 hours, from Monday to Saturday. Thus, a single crew member works 72 hours a week. In the conducted case study it is expected that the well can be established in the time from Monday to Saturday, thus within 6 days.
- The project´s timeline is structured as follows. On Monday the drilling crew and the machinery are transported to the drilling site. On Tuesday the drilling site is prepared, the rig assembled and drilling initiated. From Wednesday to Friday the drilling, the installation of the casing and the probe, and the cementing are conducted. On Saturday the drilling site is dismantled. The relocation of the drilling crew and the machinery is booked on the subsequent project.[223]
- The drilling crew required for this project consists of seven people, one driller, one assistant driller, four drilling associates, and one drilling mud associate. Craftsmen

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[222] To reflect the project as realistically as possible, the case study is executed with the assistance of Mr. Detlef Schellenberg, controller at MB Well Services GmbH, and Mrs. Doreen Koennecke, project manager at MB Well Services GmbH.
[223] Refer to Koennecke, D.; (2023), personal communication

like electricians, mechanics, or locksmiths are not part of the crew but stay at the company´s base and are called to the drilling site in case of need.[224] To be able to calculate the according personnel costs, it is acted on the assumption that the crew is German. According to this, German standards respectively the standards of MB Well Services GmbH are consulted for calculating the personnel costs.

- For simplification purposes, it is assumed that the rig is used to its full capacity over the year. Concretely, this means that the rig operates 50 weeks a year, thus realizing 50 projects of one-week length in one year. This assumption is necessary to be able to distribute certain costs aliquot to the single projects.
- Concerning the energy consumption of the rig and its auxiliary machinery, it is assumed that all equipment is powered by diesel. Although operating in an urban area, where electrical power supply is available, no equipment is connected to the electricity grid. Furthermore, it is assumed that all powered equipment operates at 60% of its full capacity during operating hours. Assuming such an average degree of capacity utilization is necessary because in practice the degree of utilization varies significantly among different drilling activities and stages.[225]

Generally, the project costs consist of the five cost groups personnel, equipment, material, miscellaneous and overhead costs. By means of the following tables, formulas, and explanations, it is presented how the costs of the particular groups are made up. At the end of this chapter, all five cost groups are consolidated.

3.2.1 Personnel costs

Table 5 lists how the salaries of the drilling crew accumulate. The salary of a crew member composes of an hourly rate plus allowances. Additionally, an aliquot for extra costs that an employee causes the company is included. Examples for origins of these extra costs are training, workwear, or holiday allowance. The mast allowance can be understood as a danger bonus for the crew members that are working in the mast, hence in heights. As Table 5 shows, the salaries for one week accumulate to 20.448,47€.

[224] Refer to Eibl, J.; (2023), personal communication
[225] Refer to Wirth, S.; (2023), personal communication

Table 5: Drilling crew salaries[226]

Job title	Driller	Assistant driller	Drilling associate	Drilling mud associate	**Total**
Number	1	1	4	1	
Hourly rate without allowances	41,31€	38,98€	34,71€	38,98€	
Shift allowance per hour	1,37€	1,29€	1,14€	1,29€	
Mast allowance per hour	0,00€	0,00€	2,28€	0,00€	
Total allowances	1,37€	1,29€	3,42€	1,29€	
Hourly rate with allowances	42,68€	40,27€	38,13€	40,27€	
Aliquot for extra costs	1,66€	1,66€	0,99€	0,99€	
Total costs per hour	44,33€	41,92€	39,12€	41,26€	
Working hours per week	72	72	288	72	
Total costs per week	3.192,08€	3.018,29€	11.267,49€	2.970,61€	**20.448,47€**

The project´s personnel costs not only consist of the salaries but also of costs caused by accommodation, subsistence, and transfer. Table 6 presents the crew´s accommodation costs for six overnight stays, so from Monday to Sunday. This weekly accommodation costs accumulate to 2.100€.

Table 6: Accommodation costs[227]

Job title	**Number**	**Number of overnight stays**	**Total number of overnight stays**	**Costs per overnight stay**	**Accommodation costs per week**
Driller	1	6	6	50,00€	300,00€
Assistant driller	1	6	6	50,00€	300,00€
Drilling associates	4	6	24	50,00€	1.200,00€
Drilling mud associate	1	6	6	50,00€	300,00€
Total					**2.100,00€**

For the six days of operation, every crew member gets a daily subsistence allowance of 28€. As Table 7 images, the weekly subsistence costs account for 1.176€.

[226] Refer to Schellenberg, D.; (2023), personal communication
[227] Refer to Schellenberg, D.; (2023), personal communication

Table 7: Subsistence costs[228]

Job title	Number	Number of subsistence allowances	Total number of subsistence allowances	Costs per subsistence allowance	Subsistence allowances per week
Driller	1	6	6	28,00€	168,00€
Assistant driller	1	6	6	28,00€	168,00€
Drilling associates	4	6	24	28,00€	672,00€
Drilling mud associate	1	6	6	28,00€	168,00€
Total					**1.176,00€**

The last component of personal costs is the transfer costs for the drilling crew. These costs relate to the transfer of the single crew members from the company´s base to the drilling site and vice versa. As Table 8 indicates, the crew members travel 250 kilometers, thus total costs of 1.050€ generate.

Table 8: Transfer costs[229]

Job title	Number	Number of transfers per week	Distance per transfer	Costs per kilometer	Transfer costs per week
Driller	1	2	250,00km	0,30€	150,00€
Assistant driller	1	2	250,00km	0,30€	150,00€
Drilling associates	4	2	250,00km	0,30€	600,00€
Drilling mud associate	1	2	250,00km	0,30€	150,00€
Total					**1.050,00€**

Accumulated, the total personnel costs including salaries, accommodation, subsistence, and transfer amount to 24.774,47€.

3.2.2 Machinery and equipment costs

The next cost group deals with the costs related to the applied equipment and machinery. Concretely, this group comprises costs that generate due to repair, maintenance, revision, inspection, and similar activities. According to experience, a rig of the dimension of the converted AM12/50 causes mean costs regarding these activities of 250.000€ per year. Divided among the 50 projects per year, the costs per project linked to repair, maintenance, revision, and inspection account for 5.000€.[230] In addition, this cost group

[228] Refer to Schellenberg, D.; (2023), personal communication
[229] Refer to Schellenberg, D.; (2023), personal communication
[230] Refer to Schellenberg, D.; (2023), personal communication

also considers imputed depreciation and imputed interests. Table 9 presents the various equipment for which imputed depreciations and interests are calculated, while Table 10 presents the calculated values.

Table 9: List of equipment[231]

Equipment	**Costs of purchase**	**Operating life time [years]**	**In-house availability**
Rig AM12/50	1.350.000,00€	25	yes
Mud pump	800.000,00€	25	no
Mud tanks	125.000,00€	25	no
Shale shaker	150.000,00€	25	no
Drill pipes	64.675,00€	3	no
Drill collars	31.314,00€	3	no
Drill bits	16.200,00€	1	no
BOP including a spool and flange	40.000,00€	15	no
Rotary table	160.000,00€	15	no
3x Master bushing	11.000,00€	15	no
Rotary head	47.500,00€	15	no
Power unit for rotary head	11.000,00€	15	no
2x Power tongs	70.000,00€	10	no
3x Slips	1.800,00€	10	no
Team and sanitary container	80.000,00€	8	yes
High-pressure elements, manifold, and other small components	45.000,00€	8	yes
Forklift 6,5t	75.000,00€	8	yes
2x Diesel generator set	4.000,00€	10	no
Total	**3.082.489,00€**		

As can be seen in Table 9, the list of equipment comprises more equipment than covered in Chapter 3.1.3. This is because, in Chapter 3.1.3 only equipment that needs to be bought in addition is covered, thus the CAPEX can be obtained. However, to be able to operate with the rig, more equipment is required that is already available in-house, since it is also of need when performing workover activities. Thus, the imputed depreciation and interest can be calculated as precisely as possible, all equipment that is used during operation needs to be considered.

Imputed depreciation records the depreciation, thus the loss in value, of equipment that is not used up within an accounting period (as mentioned in the assumptions above, it is one week) in the cost calculation. In this case, the accounting period is one week since this is the project´s duration, as mentioned in the assumptions above. In contrast to the depreciation on the balance sheet, which is regulated in commercial and tax law, the imputed depreciation can be used to try to determine the equipment´s operating life time as accurately as possible. Accordingly, it can be set at any level.[232] To be able to

[231] Refer to Schellenberg, D.; (2023), personal communication
[232] Refer to Betriebswirtschaft-lernen, https://www.betriebswirtschaft-lernen.net/en/explanation-2/imputed-depreciation/ (accessed: 10.07.2023)

calculate the imputed depreciation of certain equipment, it is necessary to know the equipment´s original cost of purchase and to determine its expected operating life time. With these data (presented in Table 9) and by estimating the inflation (3% in this case), thus the rise in prices over the equipment´s operating life time, the equipment's replacement value at the end of its operating life time can be computed. After its operating life time it is assumed that the equipment has a terminal value of 0€. To calculate the replacement value, the following formula is applied.

$$Replacement\ value = Cost\ of\ purchase * 1{,}03^{Operating\ life\ time}$$

As an example, the calculation of the AM12/50´s replacement value is presented. The calculations of the remaining equipment's replacement values are analog.

$$Replacement\ value\ (AM12/50) = 1.350.000€ * 1{,}03^{25} = 2.826.600{,}21€$$

The yearly imputed depreciation is calculated by dividing the replacement value by the operating life time.

$$Annual\ imputed\ depreciation = \frac{Replacement\ value}{Operating\ life\ time}$$

As shown in Table 10, the single equipment´s imputed depreciations are accumulated to obtain the total annual imputed depreciation of 324.593,34€. Dividing this figure by the annual project number of 50 results in a project-related imputed interest of 6.491,87€.

Besides the imputed depreciation, also the imputed interests are considered in the machinery-related cost calculation as part of the imputed costs. This is because the company invests in equipment instead of investing in the capital market. For this reason, the company misses out on potential interests. By taking imputed interests, thus fictitious interests, into account and passing them on to the client, the shortfall in interests is absorbed. Imputed interests are calculated by multiplying the acquisition costs of equipment with a certain interest rate. The imputed interest of an individual equipment is taken into account in the cost calculation as long as it is in use. If a particular equipment is discarded and repurchased, imputed interest will be recalculated, based on the actual purchase price. This means that the imputed costs calculated in this case study are valid until an equipment is newly acquired with a purchase price that differs from the previous one.[233] In the course of this case study, an interest rate of 4% is used.

$$Imputed\ interest = Costs\ of\ purchase * Interest\ rate$$

[233] Refer to BWL- Lexikon, https://www.bwl-lexikon.de/wiki/kalkulatorische-zinsen/ (accessed: 10.07.2023)

As an example, the calculation of the AM12/50´s annual imputed interest is presented. The calculations of the remaining equipment’s annual imputed interests follow the same procedure.

$$Annual\ imputed\ interest\ (AM12/50) = 1.350.000{,}00€ * 0{,}04 = 54.000{,}00€$$

As shown in Table 10, the single equipment´s interests are summed up to obtain the total annual imputed interest of 123.299,56€. Dividing this figure by 50 results in a project-related imputed interest of 2.465,99€.[234]

Table 10: Value of replacement, imputed depreciation, and imputed interest[235]

Equipment	**Replacement value after operating life time**	**Annual imputed depreciation**	**Annual imputed interest**
Rig AM12/50	2.826.600,21€	113.064,01€	54.000,00€
Mud pump	1.675.022,34€	67.000,89€	32.000,00€
Mud tanks	261.722,24€	10.468,89€	5.000,00€
Shale shaker	314.066,69€	12.562,67€	6.000,00€
Drill pipes	70.672,12€	23.557,37€	2.587,00€
Drill collars	34.217,65€	11.405,88€	1.252,56€
Drill bits	16.686,00€	16.686,00€	648,00€
BOP including a spool and flange	62.318,70€	4.154,58€	1.600,00€
Rotary table	249.247,79€	16.618,32€	6.400,00€
3x Master bushing	17.137,64€	1.142,51€	440,00€
Rotary head	74.003,45€	4.933,56€	1.900,00€
Power unit for rotary head	17.137,64€	1.142,51€	440,00€
2x Power tongs	94.074,15€	9.407,41€	2.800,00€
3x Slips	2.419,05€	241,90€	72,00€
Team container and sanitary container	101.341,61€	12.667,70€	3.200,00€
High-pressure elements, manifold, and other small components	57.004,65€	7.125,58€	1.800,00€
Forklift 6,5t	95.007,76€	11.875,97€	3.000,00€
2x Diesel generator set	5.375,67€	537,57€	160,00€
Total (annually)	5.974.082,35€	**324.593,34€**	**123.299,56€**
Total (project-related)	5.974.082,35€	**6.491,87€**	**2.465,99€**

In total, the machinery and equipment-related costs accumulate to 13.957,86€.

[234] Refer to Schellenberg, D.; (2023), personal communication
[235] Refer to Schellenberg, D.; (2023), personal communication

3.2.3 Material costs

The next cost group which is to be covered deals with the consumption of materials. Namely, these materials are the casing, the cement, and the probe. As already mentioned, the outlined well is cased and cemented to its full depth of 700 meters. Casings are available in many different qualities because they need to be adjusted to the characteristics of the borehole. For this case study, the casing´s price is rated to be 600€ per ton, which is a realistic average value.[236] Hence, the material costs for the casing with a weight of 37.177 kilograms result in 22.306,2€. The probe that is to be installed is 1.400 meter in length. It runs to the well´s total depth, makes a u-turn, and returns to the surface. A typical probe, used for such purposes, is a PE probe with an outside diameter of 40 millimeters and a wall thickness of 3,7 millimeters. Such a probe costs 2,60€ per meter so 1.400 meters cost 3.640€.[237] Since the wellbore is completely filled with cement, the required volume of cement is calculated by subtracting the casing volume (4,63m^3) and the probe volume (1,76m^3) from the borehole volume (53,23m^3). Thus, the volume of cement that is required results in 46,84m^3. Regarding the price of cement, the mean value of 125€ per m^3 is used. Similar to the casing, different qualities of cement exist that vary in price. The material costs for cement, therefore, amount to 5.855€. Costs for pumping the cement into the borehole, additionally, cause costs of around 1.000€, so that costs regarding the cement accumulate to 6.855€.[238]

Aggregated, the material costs amount to 32.801,20€.

3.2.4 Miscellaneous costs

The next cost group is called miscellaneous costs since costs of different natures are consolidated. These costs arise due to the removal of waste and feces, transport of equipment, and diesel consumption.

For the removal of waste and feces, MB Well Services GmbH follows the practice of estimating the according costs in the amount of 5€ per hour of operation. In this case, the operation continues for six days with 12 working hours each, so the total costs regarding the removal of waste and feces accumulate to 360€.[239]

The next cost unit that needs to be covered is the logistics for the equipment. Table 11 presents the estimation regarding the number of required truckloads.[240]

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[236] Refer to Made in China, https://www.made-in-china.com/quality-china-product/productSearch?word=casing+9+5%2F8 (accessed: 10.07.2023)

[237] Refer to Pumpe 24, https://www.pumpe24.de/pe100-rohr-40-x-3-7mm-ringbund-a-25m-dvgw.html (accessed: 10.07.2023)

[238] Refer to Transportbeton Eder GmbH, https://www.eder.co.at/fileadmin/user_upload/downloads-beton/preisliste-beton.pdf (accessed: 10.07.2023)

[239] Refer to Schellenberg, D.; (2023), personal communication

[240] Mrs. Koennecke, project manager at MB Well Services, assisted in estimating the required truckloads to transport all the required equipment from the company´s base to the drilling site.

Table 11: Truckloads required to transport the equipment[241]

Equipment	Number of truckloads
Rig AM12/50	driving independently
Mud pump	0,5
Mud tanks	2
Shale shaker	accumulative load
Casings	3
Drill pipes	2
Drill collars	1
Drill bits	accumulative load
BOP including a spool and flange	accumulative load
Rotary table	1
3x Master bushing	accumulative load
Rotary head	accumulative load
Power unit for rotary head	accumulative load
2x Power tongs	accumulative load
3x Slips	accumulative load
Team container and sanitary container	1
High-pressure elements, manifold, and other small components	0,5
Forklift 6,5t	0,5
Diesel generator set	0,5
Total	**13**

As presented in Table 11, 13 truckloads are required to transport the equipment. However, this is only valid for transport from the company´s base to the drilling site. When transporting the equipment the other way, only 10 truckloads are needed, since the casing gets installed. Thus, 23 truckloads are required in total. A truckload of 250 km in one direction costs 750€, thus the total costs for the transport accumulate to 17.250€. Additionally, a crane is required at the site to manipulate the heavy equipment. It is assumed that this crane operates 12 hours for assembling the site and another 12 hours for dismantling the drilling site. With an hourly rate of 125€, the crane causes additional costs of 3.000€. Hence, the total costs for logistics amount to 20.250€.[242]

The necessary assumptions regarding the diesel consumption of the rig´s machinery, have already been mentioned. However, it needs to be mentioned that the calculated consumption serves as a guide value, the actual consumption is only known when the operation is finalized. To be able to compute the costs concerning the expected diesel consumption, the required information is the total capacity of the machinery, the degree of utilization, the diesel equivalent of kWh, and the current diesel price. Table 12 lists the diesel-driven machinery and the according capacities.

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[241] Refer to Koennecke, D.; (2023), personal communication
[242] Refer to Koennecke, D.; (2023), personal communication

Table 12: Equipment and capacities

Equipment	AM12/50	Mud pump	Hydraulic power unit	2x Diesel generator sets	Forklift	**Total**
Capacity	280kW[243]	446kW	50kW[244]	10kW	42kW[245]	**828kW**

Extrapolated to the project´s 72 operating hours and in consideration of the 60% utilization degree, the machinery consumes 35.769,60kWh. Applying an equivalent of 10,3 kWh per liter of diesel, the diesel consumption for the outlined project amounts to 3.472,78 liters.[246] Currently, the net price of diesel is 1,23€, thus the week-long project causes diesel costs in the amount of 4.271,52€.[247]

Summarized, the total miscellaneous costs regarding the removal of waste and feces, the equipment´s logistics, and the diesel consumption accumulate to 24.774,47€.

3.2.5 Total OPEX

After introducing the different cost groups and explaining their composition, a complete cost report is presented in Table 13. This complete cost report summarizes the costs of the four previously presented cost groups to get the project-related OPEX. Additionally, a surcharge for overhead costs is incorporated into the cost report. In the drilling industry, it is common practice, to put a simplified overhead costing into effect. MB Well Services GmbH, for example, additionally, allocates 23% of the project-related OPEX as overhead rate. In this case study, the same procedure is applied. The overhead rate is supposed to cover all costs that accrue due to operating activities away from the drilling site. Examples of these activities are project management, sales and marketing, various back office activities, or health, safety, and environment (HSE). The sum of project-related OPEX and the surcharge for overhead costs results in the total OPEX. To, finally, obtain the costs the client is facing, another surcharge needs to be included in the calculation. Namely, this surcharge is the company´s profit margin and is supposed to provide profit to the company, cushion potential risks, and cover profit tax. The profit margin, usually, varies among projects and also serves as a room for negotiating with the client. In the course of this case study, the profit margin is fixed at 15% of the project costs.[248]

Table 13 presents the complete cost report.

[243] Refer to Confind S.R.L.(w.rd.), page 5 pp.
[244] Refer to Wirth, S.; (2023), personal communication
[245] Refer to Jungheinrich AG, https://media-live2.prod.scw.jungheinrichcloud.com/resource/blob/1377000/af812854e111ee7f1c39c6c1c7e8301e/efg-5-specsheet-de-2023-07-pdf-data.pdf (accessed: 11.07.2023)
[246] Refer to Energie-Lexikon, https://www.energie-lexikon.info/dieselkraftstoff.html (accessed: 11.07.2023)
[247] Refer to ÖAMTC, https://www.oeamtc.at/routenplaner/poi/tanken/1210287?lat=48.202627259999986&long=16.36841764999997&zoom=12 (accessed: 11.07.2023)
[248] Refer to Schellenberg, D.; (2023), personal communication

Table 13: Complete cost report[249]

Category	**Costs [€]**
Personnel costs	
Salaries	20.448,47
Accommodation	2.100,00
Subsistence allowance	1.176,00
Kilometer allowance	1.050,00
Subtotal	*24.774,47*
Equipment costs	
Flat rate for repair, maintenance, revision, inspection, etc.	5.000,00
Imputed depreciation	6.491,87
Imputed interest	2.465,99
Subtotal	*13.957,86*
Material costs	
Casing	22.306,20
Cement	6.855,00
Probe	3.640,00
Subtotal	*32.801,20*
Miscellaneous costs	
Diesel fuel	4.271,52
Logistics	20.250,00
Flat rate for removal of waste, feces, etc.	360,00
Subtotal	*24.881,52*
Project-related OPEX	**96.415,05**
Surcharge for overhead costs (23%)	22.175,46
Total OPEX	**118.590,51**
Surcharge for profit, risk, and profit tax (15%)	17.788,58
Project costs for the client	**136.379,08**

[249] Refer to Schellenberg, D.; (2023), personal communication

As highlighted in Table 13, a client who commissions the establishment of the outlined well needs to procure 136.379,08€. At this stage, it needs to be stated that the services of setting the conductor and completing the geothermal probe on the surface are not included in the presented sum. The final costs for the client, therefore, are higher than 136.379,08€. Not considered in this calculation is the value-added tax. This is because potential clients for such projects are rather businesses than private persons and businesses are excluded from paying value-added taxes in Austria and Germany.

3.3 Key performance indicators

In this chapter, the previously compiled results are processed into adequate key performance indicators (KPIs). The analysis and the assessment of these KPIs are then conducted in Chapter 4.

Generally, different categories of KPIs exist. Examples are KPIs regarding timeliness, finances, quality, and effectiveness. In the course of this chapter, only financial KPIs are covered. First, it needs to be determined, which KPIs are the most useful and meaningful for this cause. Normally, KPIs are chosen according to the company's respectively the project´s goals. Since, in this case, only a restricted quantity of data is available, the selection of expressive KPIs yields on its own. In the following passage, KPIs regarding the conversion of the AM12/50 rig are presented.

CAPEX

This KPI is a total number, representing the total capital expenditures. Capital expenditures are funds used to acquire, upgrade, and maintain physical items.[250] In this case, the CAPEX refer to the investment that needs to be made to convert the AM12/50 into a drillable rig. As calculated in Chapter 3.1.3, the CAPEX accumulate to 1.532.489€.

OPEX

Equal to the CAPEX, this KPI is a total number and represents the total operating expenses. In this case, the OPEX relate to the costs that accrue when realizing a project as outlined with the converted AM12/50. Registered in Chapter 3.2 these operating costs amount to 118.590,51€. To calculate the annual OPEX, assumptions need to be made. First, it is assumed that the AM12/50 is operating to its full capacity over the year. Second it is assumed that all projects are identical, hence, have the same sales price. Concretely, this means that 50 projects are realized per year, while every single project accounts OPEX of 118.590,51€. Therefore, the annual OPEX accumulate to 5.929.525,50€.

Sales price

This KPI is computed in Chapter 3.2 and depicts the costs the client is facing for the service. Concretely, the sales price amounts to 136.379,08€. If the client is a private person, the sales price increases to 163.654,90€ because the value-added tax of 20% needs to be considered. Different approaches to determining the sales price exist. The quoted sales price is calculated with the "cost-plus pricing" strategy, which uses OPEX to sell the service with a fixed percentage added to the total. Essentially, a profit margin of 15% is applied. Another pricing strategy, for example, is "competitive pricing" where prices of similar services from competitors are considered and used to determine the

[250] Refer to Investopedia, https://www.investopedia.com/terms/c/capitalexpenditure.asp (accessed: 19.07.2023)

sales price. Generally, the pricing of a service requires the consideration of costs and what the market bears. Besides quality, the sales price is the most important feature of the service, since both are decision criteria for the client. When the sales price is too low, the profit margin is diminished, when the sales price is too high, the clients are deterred.[251]

Revenue

This KPI can be defined as the money generated from business operations. It is calculated by multiplying the sales price times the number of units sold within a certain period.[252] The revenue made with one project can be read from Table 13, it amounts to 136.379,08€. To calculate the potential annual revenue that can be made with the converted AM12/50, again it is assumed that 50 identical projects are realized per year. Thus, the annual revenue is calculated as follows.

$$Annual\ revenue = 50 * 136.379{,}08€ = 6.818.954{,}00€$$

Gross profit

This is the profit a company makes after subtracting the costs associated with making a product or providing a service. Thus, the gross profit highlights the project-related variable costs that, in practice, vary among projects. Thus, gross profit assesses the efficiency regarding the application of labor and supplies in producing goods or services.[253] In this case, when calculating the gross profit for a single project, the project-related OPEX (designated in Table 13) are deducted from the revenue.

$$Gross\ profit\ per\ project = 136.379{,}08€ - 96.415{,}05€ = 39.964{,}03€$$

The yearly gross profit is calculated by assuming that 50 projects are realized within a year.

$$Annual\ gross\ profit = 50 * (136.379{,}08€ - 96.415{,}05€) = 1.998.201{,}50€$$

Gross Profit margin

This KPI is useful for comparing the production efficiency, thus, the application of resources, over time. Comparing gross profits from different periods or projects can be misleading since gross profits can rise while gross margins fall. Simply expressed,

[251] Refer to Forbes, https://www.forbes.com/sites/forbesbusinesscouncil/2022/08/22/understanding-pricing-strategies-price-points-and-maximizing-revenue/ (accessed: 19.07.2023)
[252] Refer to Investopedia, https://www.investopedia.com/terms/r/revenue.asp (accessed: 20.07.2023)
[253] Refer to Investopedia, https://www.investopedia.com/terms/g/grossprofit.asp (accessed: 20.07.2023)

earning a higher gross profit does not mean that the resources were applied more efficiently, and this can be verified by the gross profit margin.[254] The gross profit margin gives a percentage and is calculated as follows.

$$Gross\ profit\ margin = \frac{Revenue - Project\ OPEX}{Revenue} * 100^{255}$$

$$Gross\ profit\ margin = \frac{136.379{,}08€ - 96.415{,}05€}{136.379{,}08€} * 100 = 29{,}30\%$$

Earnings before interest and taxes (EBIT)

In contrast to the gross profit, this KPI also considers the overhead costs that are not directly linked to the project. EBIT is calculated as revenue minus expenses excluding tax and interest, therefore, indicates the profitability of a company. Interests in connection with EBIT are interests in debt capital and not imputed interests.

$$EBIT = Revenue - Project\ costs - Overhead\ costs^{256}$$

$$Project\ EBIT = 136.379{,}08€ - 96.415{,}05€ - 22.175{,}46€ = 17.788{,}57€$$

$$Annual\ EBIT = 50 * (136.625{,}69€ - 96.589{,}39€ - 22.215{,}56€) = 889.428{,}50€$$

Earnings before interest, taxes, depreciation, and amortization (EBITDA)

This KPI is similarly calculated as the EBIT, except that it also excludes depreciation and amortization when computing the earnings. For a company with a significant amount of fixed assets, which applies in this case, depreciation impacts net income. On that account, EBITDA measures a company's profits by removing depreciation and reveals the profitability of a company's actual operational performance.[257]

$$EBITDA = EBIT + Depreciation\ costs$$

$$Project\ EBITDA = 17.788{,}57€ + 6.491{,}87€ = 24.280{,}44€$$

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[254] Refer to Investopedia, https://www.investopedia.com/terms/g/grossprofit.asp (accessed: 20.07.2023)

[255] Refer to Investopedia, https://www.investopedia.com/terms/g/grossprofit.asp (accessed: 20.07.2023)

[256] Refer to Investopedia, https://www.investopedia.com/terms/e/ebit.asp (accessed: 20.07.2023)

[257] Refer to Investopedia, https://www.investopedia.com/terms/e/ebitda.asp (accessed: 20.07.2023)

$$Annual\ EBITDA = 50 * (17.820{,}74€ + 6.666{,}21€) = 1.214.022{,}00€$$

Net Profit

This KPI differs from gross profit by also considering the fixed costs and it differs from EBITDA because it also considers interests, taxes, and depreciation and amortization costs. Net profit is the income that remains after all expenses and costs have been deducted from revenue, which is why it is often called “the bottom line”. It gives information about the overall profitability, which reflects how effectively a company is managed.[258] To be able to compute the net profit, it needs to be determined in which country the company is subject to taxation since tax systems vary among countries. For this purpose, it is assumed that the company is declarable in Austria respectively Germany. Due to simplification only the corporate income tax is considered in the following calculations. Taxes of significantly lower rates, like municipal tax, are ignored regarding their minor influence on the results. Corporate income tax in Austria accounts for 24% of the EBIT.[259] In Germany the corporate income tax accounts for 15% but a solidarity tax of 5,5% is added, so in total 20,5% of the EBIT are due.[260]

$$Net\ profit = EBIT * (100\% - Corporate\ income\ tax)$$

$$Project\ net\ profit\ (Austria) = 17.788{,}57€ * (100\% - 24\%) = 13.519{,}31€$$

$$Annual\ net\ profit\ (Austria) = 50 * 13.519{,}31€ = 675.965{,}50€$$

$$Project\ net\ profit\ (Germany) = 17.788{,}57€ * (100\% - 20{,}5\%) = 14.141{,}91€$$

$$Annual\ net\ profit\ (Germany) = 50 * 14.141{,}91€ = 707.095{,}50€$$

Cash flow (CF)

This KPI relates to the net amount of cash and cash equivalents being transferred in and out of a company. Thereby, inflows represent cash received, while outflows represent money spent. For a company, it is fundamental to generate positive cash flows. A positive cash flow indicates that a company increases its liquid assets, allowing it to cover obligations, reinvest in its business, return money to shareholders, pay expenses, and provide a cushion against future financial challenges. Different methods to determine the cash flow exist. In this case, the cash flow is calculated by using the net profit. Non-cash

[258] Refer to Investopedia, https://www.investopedia.com/ask/answers/101314/what-are-differences-between-gross-profit-and-net-income.asp (accessed: 20.07.2023)
[259] Refer to WKO, https://www.wko.at/service/steuern/Koerperschaftsteuer_(KOeSt).html (accessed: 20.07.2023)
[260] Refer to Haufe, https://www.haufe.de/thema/koerperschaftsteuer/ (accessed: 20.07.2023)

costs like imputed depreciation and interest are added to the net profit to obtain the cash flow.[261]

$$Annual\ CF = Annual\ net\ profit + \ annual\ imputed\ costs$$

$$\text{Annual CF (Austria)} = 675.965{,}50€ + 50 * (6.491{,}87€ + 2.465{,}99€) = 1.123.858{,}50€$$

$$Annual\ CF\ (Germany) = 707.095{,}50€ + 50 * (6.491{,}87€ + 2.465{,}99€) = 1.154.988{,}50€$$

Return on investment (ROI)

Return on investment is a key performance indicator used to evaluate the profitability of an investment. ROI measures the amount of return on a particular investment, relative to the costs of the investment. It is calculated by dividing the investment's net profit (or loss) by its initial costs and is expressed as a percentage. Because ROI is measured as a percentage, it serves as a very expressive reference value for different investments. That way, the profitability of a variety of investments can be compared against each other. If a ROI classifies as “good” depends on factors like the risk tolerance of the investor or the time required for the investment to pay off. Investors who are more reluctant to risk accept rather low ROIs in exchange for taking less risk. On the contrary, investments that take longer to generate returns require a higher ROI in order to attract investors. To get an idea of the ROI´s dimension, the average ROI for the Standard & Poor´s 500, which accounts for around 10%, can be mentioned. The Standard & Poor's 500 Index, is an index covering the 500 leading publicly traded companies in the United States of America.[262]

To calculate the ROI of the investment for the conversion of the AM12/50, the following formula is applied.

$$ROI = \frac{Annual\ net\ profit}{Costs\ of\ investment\ (CAPEX)} * 100$$

$$ROI\ (Austria) = \frac{675.965{,}50€}{1.532.489€} * 100 = 44{,}11\%$$

$$ROI\ (Germany) = \frac{707.095{,}50€}{1.532.489€} * 100 = 46{,}14\%$$

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261 Refer to Investopedia, https://www.investopedia.com/terms/c/cashflow.asp (accessed: 21.07.2023)

262 Refer to Investopedia, https://www.investopedia.com/terms/r/returnoninvestment.asp (accessed: 21.07.2023)

Payback period

This KPI refers to the amount of time it takes to recover the costs of an investment. Generally, the shorter the payback period of an investment is, the more attractive it is. Determining the payback period in years is done by dividing the initial investment by the annual cash flow.[263]

$$Payback\ period = \frac{Costs\ of\ Investment}{Annual\ cash\ flow}$$

$$Payback\ period\ (Austria) = \frac{1.532.489€}{1.123.858{,}50€} = 1{,}36\ years\ [\sim 1\ year\ and\ 6\ months]$$

$$Payback\ period\ (Germany) = \frac{1.532.489€}{1.154.988{,}50€} = 1{,}33\ years\ \ [\sim 1\ year\ and\ 6\ months]$$

The calculated payback periods only serve as guide values and are not completely correct. This is because the drill bits which are of relatively low purchase costs have a shorter operating life time than the calculated payback period. Hence, the drill bites need to be replaced before the payback period elapses.

Price per meter drilled

Opposite to the previously presented key performance indicators, this last KPI is not a well-established one. Nevertheless, the price per meter drilled is very expressive in this context because it enables an impactful comparison with the competition. Concretely, this KPI refers to the price the client is facing per meter drilled. The base of this KPI is the project´s sales price which is divided by the total drilling depth.

$$Price\ per\ meter\ drilled = \frac{Sales\ price}{Total\ drilling\ depth}$$

$$Price\ per\ meter\ drilled = \frac{136.379{,}08€}{700m} = 194{,}83\ €/m$$

Certainly, it is also possible to compare the sales price with competition, however, because projects are very individual and rarely equal, the meaningfulness is constricted. Comparing the price per meter drilled is a more expressive method since it is decoupled from the drilling depth, which is variable among projects.

263 Refer to Investopedia, https://www.investopedia.com/terms/p/paybackperiod.asp (accessed: 21.07.2023)

Summary

For clarity reasons, Table 14 summarizes all determined KPIs concerning the conversion and the utilization of the AM12/50.

Table 14: Conversion and operation KPIs of the AM12/50

KPI	Austria	Germany
CAPEX	1.532.489,00€	1.532.489,00€
Project´s OPEX	118.590,51€	118.590,51€
Annual OPEX	5.929.525,50€	5.929.525,50€
Project´s net sales price	136.379,08€	136.379,08€
Project´s revenue	136.379,08€	136.379,08€
Annual revenue	6.818.954,00€	6.818.954,00€
Project´s gross profit	39.964,03€	39.964,03€
Annual gross profit	1.998.201,50€	1.998.201,50€
Gross profit margin	29,30%	29,30%
Project´s EBIT	17.788,57€	17.788,57€
Annual EBIT	889.428,50€	889.428,50€
Project´s EBITA	24.280,44€	24.280,44€
Annual EBITDA	1.214.022,00€	1.214.022,00€
Project´s net profit	13.519,31€	14.141,91€
Annual net profit	675.965,50€	707.095,50€
Annual cash flow	1.123.858,50€	1.154.988,50€
Return on investment	44,11%	46,14%
Payback period	1 year and 6 months	1 year and 6 months
Price per meter drilled	194,83 €/m	194,83 €/m

3.4 Sensitivity analysis

This chapter is seamlessly connected with the previous chapters because it also deals with capital expenditures (CAPEX) and operating expenses (OPEX). In this chapter, sensitivity analyses are presented that demonstrate what influence a single cost position has on the total costs. Therewith, it is highlighted which cost positions require particular attention.

In the following, two diagrams are shown, which analyze the sensitivities of the previously computed CAPEX and OPEX. Therefore, the different cost positions fluctuate between 70% and 130% of their actual value. Thus, it is highlighted, how the total CAPEX respectively the OPEX change, when one cost position fluctuates, while the other cost positions remain at their actual value. Concretely, each cost position is represented by a straight line and its inclination provides information about the position´s influence on the total costs. The steeper the inclination, the higher the influence is and vice versa. The data on which the following diagrams are based are shown in Appendix D.

CAPEX

Figure 50, on the next page, presents the sensitivity analysis of the CAPEX.

In Figure 50, the straight lines each represent equipment that has to be purchased as part of the conversion process. The intersection of all lines represents the current value of the CAPEX (1.532.489€).

It is obvious that the mud pump has the most influence on the total CAPEX. If the price of the mud pump changes, the CAPEX change noticeably. This fact is illustrated by the steep inclination of the green straight line in Figure 50. The reason for this is that the mud pump (800.000€ purchase costs) accounts for 52,2% of the CAPEX. In case the mud pump´s purchase costs rise by 30%, the CAPEX increase to 1.772.489€, which equates to an increase of 15,66%. In case the mud pumps´ purchase costs drop to 70% of their actual value, the CAPEX drop to 1.292.489€ (decline of 15,66%). The cost positions that also have a noticeable influence on the CAPEX, although much more minimal than the pump, are the rotary table (160.000€ purchase costs), the shale shaker (150.000€ purchase costs), and the mud tanks (125.000€ purchase costs). If their costs increase or decrease by 30%, this causes the CAPEX to increase or decrease by 3,13%, 2,93% respectively 2,45%. The remaining cost positions have a much smaller impact on the CAPEX, which is expressed by the low inclination of their straight lines.

The sensitivity analysis of CAPEX shows what effect could be achieved if savings could be made at a particular cost position. As already mentioned, there is the possibility to buy certain equipment secondhand, so that savings are possible. The analysis shows which equipment provides the greatest savings potential. If it is possible to buy the mud pump, the rotary table, the shale shaker, and/or the mud tanks secondhand and at a reduced price without having to accept any loss of quality, the CAPEX could be significantly reduced.

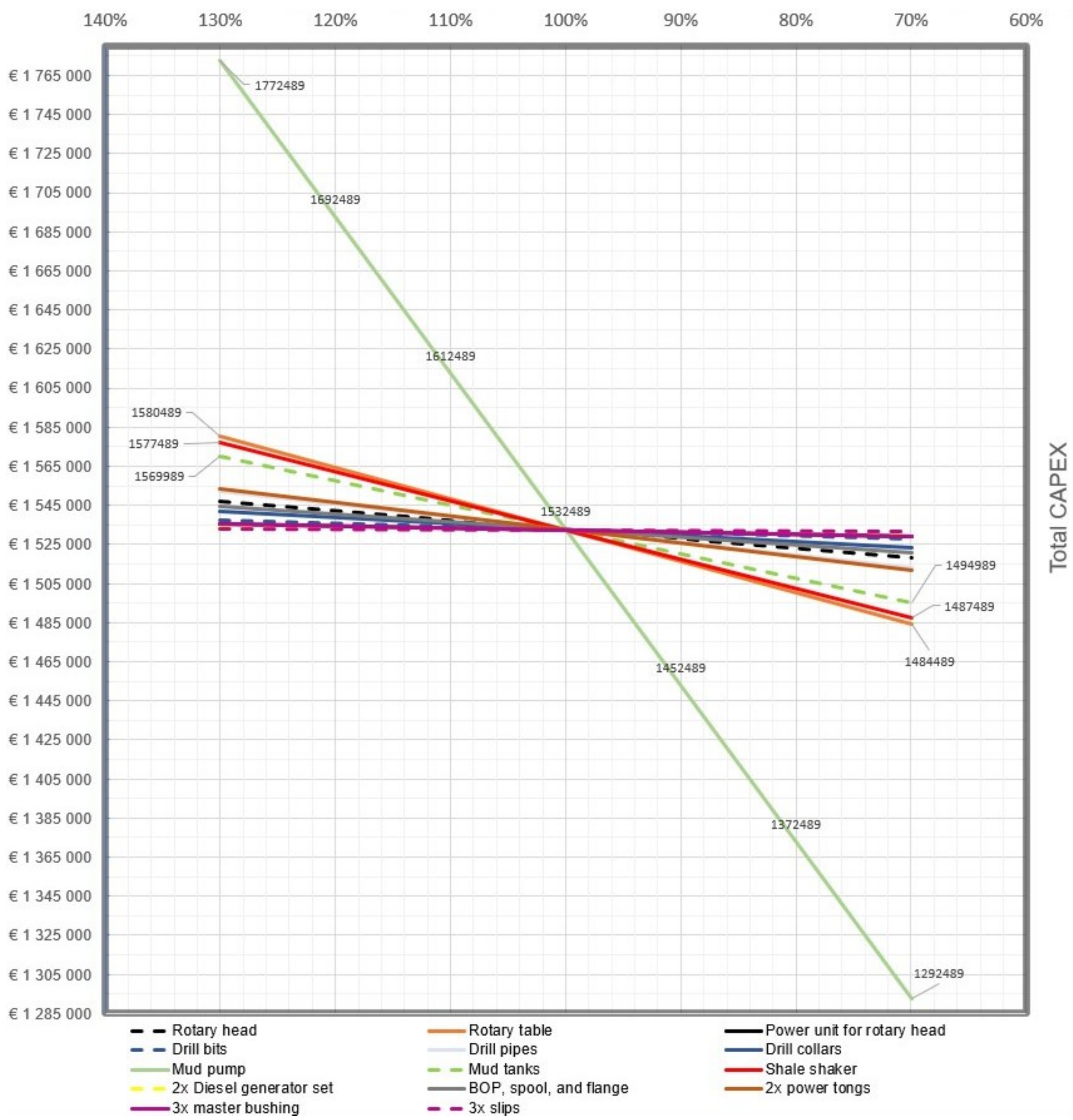

Figure 50: Sensitivity analysis of the CAPEX

OPEX

Figure 51 presents the sensitivity analysis of the OPEX.

In Figure 51, it is recognizable that the material cost group (32.801,20€) has the most influence, while the equipment cost group (13.957,86€) has the least influence. Personnel costs (24.774,47€) and miscellaneous costs (24.881,52€) almost have the same trend, since their values are of the same dimension. The intersection of all four straight lines depicts the actual project-related costs of 96.415,05€.

The maximum and the minimum value of the project-related costs arise when the most influencing cost group, the material cost group, fluctuates. In case, the material cost group rises to 130% of its actual value, the project-related costs rise to 106.255,41€. This means a 10% rise in project-related costs. When considering the surcharges for overhead costs and profit, extra costs in the amount of 13.919,20€ generate for the client due to the rise in material costs. For comparison, when the personnel costs, the miscellaneous costs, or the equipment costs rise to 130% of their actual values, extra costs of 10.513,05€, 10.558,47€ respectively 5923,01€ develop for the client. Conversely, the project-related costs lower the most, when the material costs drop in their value. When the material costs drop to 70% of their actual value, the project-related costs amount to 86.574,69€, hence decreasing by 10%. In this case, the client faces total costs of 122.459,90€, thus 13.919,18€ less than originally.

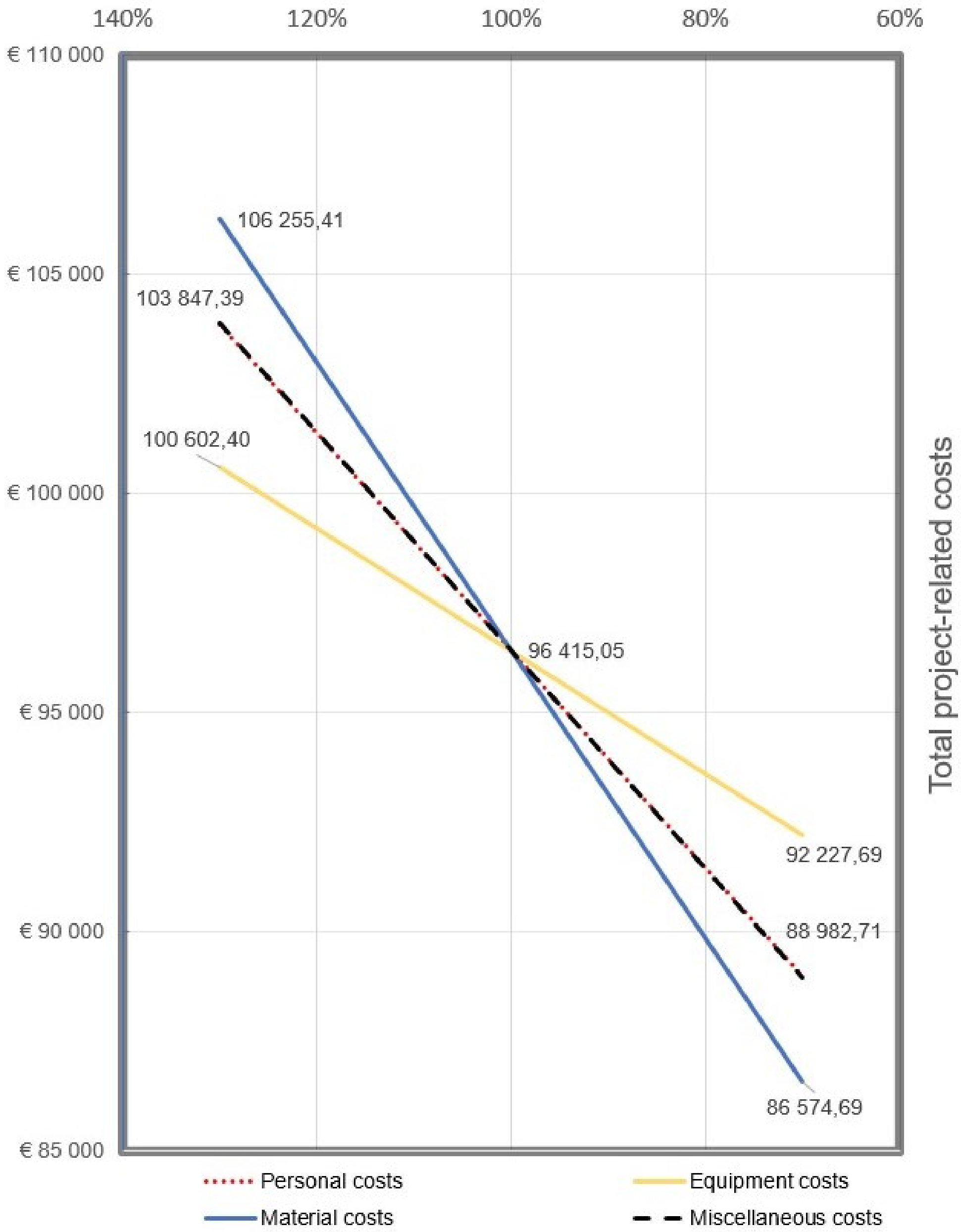

Figure 51: Sensitivity analysis of the OPEX

The sensitivity analysis of the OPEX demonstrates, to what extent the OPEX could be reduced if savings could be made in one of the four cost groups. In this case, the material costs contain potential savings. Concretely, it is possible to cut the costs regarding the casings (22.306,20€), which account for 68% of the material costs. These costs are due because in the case study, it is assumed that the total depth of the well is cased. From a cost perspective, this is the worst case. In practice, this is not necessarily required, since sometimes it is sufficient to only protect certain formations (like aquifers) by the installation of casings. For that reason, it is vital to investigate the required casing length in advance.

3.5 Gedankenexperiment towards a more sustainable drilling rig

Naturally, the application of oil and gas equipment for geothermal purposes is the central sustainability approach in this thesis. This is because, as previously explained, geothermal energy is simply a more sustainable energy source than fossil energy. However, also the development of the reservoirs, thus the drilling process, contains the potential for becoming more sustainable. When attempting to make a drilling rig more sustainable, especially, diesel fuel, as the power source for the drilling machinery, needs to be reviewed.

CO_2 balance

In the conducted case study, it is assumed that all machines of the converted drilling rig are driven by diesel fuel. This is because within the drilling industry, diesel fuel is the main power source, and the majority of drilling equipment is construed correspondingly. By reducing or even eliminating diesel consumption, CO_2 emissions can be reduced significantly or can even be eliminated. In order to realize this, it must be possible to replace diesel adequately. To get an idea of how much emissions can be eliminated by abandoning diesel fuel as the power source, the numbers from the case study, conducted in Chapter 3.2, can be taken as reference. For the outlined project, the machinery of the converted rig consumes 3.472,78 liters of diesel. Since the combustion of one liter of diesel produces around 2,62 kilograms of CO_2, the total CO_2 emissions during the one-week project accumulate to around 9,1 tons.[264] When used to its full capacity, the rig generates CO_2 emissions of approximately 455 tons per annum. For comparison, an Airbus 380, with a capacity for over 800 passengers, burns around 11,5 tons of kerosene per hour flying.[265] Therefore, the Airbus 380 hourly emits 36,34 tons of CO_2.[266] In other words, during a 12,5 hour flight, the Airbus 380 produces as much CO_2 emissions as the converted rig produces per year. This comparison highlights that the emissions of the converted rig are relatively moderate, which can be ascribed to the rig´s rather small dimension. However, large drilling rigs, with high hook load capacities of up to 900 tons, require around 5.000 liters of diesel fuel per day.[267] Assuming such a rig operates 300 days per year, it annually consumes 1.500.000 liters of diesel, hence, produces 3.930 tons of CO_2 emissions per year. Therefore, the abandonment of diesel

[264] Refer to Forrest Research, https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/carbon-emissions-of-different-fuels/ (accessed: 18.07.2023)
[265] Refer to All I know about aviation, https://alliknowaviation.com/2019/12/14/fuel-consumption-aircraft/ (accessed: 19.07.2023)
[266] Refer to Carbon Offset Guide, https://www.offsetguide.org/understanding-carbon-offsets/air-travel-climate/climate-impacts-from-aviation/co2-emissions/ (accessed: 19.07.2023)
[267] Refer to PetroWiki, https://petrowiki.spe.org/File:Devol2_1102final_Page_504_Image_0001.png (accessed: 19.07.2023)

as the power source is fundamental to making drilling rigs more sustainable. In the next passage, ideas for alternative power sources are presented.

Alternatives power sources

Generally, more and more manufacturers of drilling rigs and drilling equipment believe in electricity as the driving source. There are already drilling rigs in operation that are completely electrified. However, the reasons why electrified drilling rigs are not yet applied more comprehensively are diversified. In the following, three substantial reasons are alluded to.

- Location of drilling site: Many drilling sites are located in remote areas respectively distant from urban areas. These drilling sites are away from electrical grids, accordingly, there is no power source for electrical equipment available. Therefore, drilling machinery is applied which relies on diesel fuel as the power source.
- Costs regarding the power source: Most drilling projects are executed by oil and gas companies. These companies, in most cases, possess diesel fuel as an in-house product. Using this in-house product as the power source for drilling machinery is significantly cheaper than buying electricity as the power source. Usually, oil and gas companies, as contracting bodies, provide diesel fuel to the assigned drilling companies.
- Equipment: Given the high purchase costs of drilling machines, inspection, and maintenance, normally, are conducted regularly and diligently. Therefore, most of these machines have relatively long operating lives and only get replaced every 15 to 20 years. Due to this fact, most machinery applied in the industry still is configured to be powered by diesel fuel, since electrified machinery only recently found its way into the drilling industry.

The listed reasons for the dominance of diesel-driven machinery, actually, are valid for the oil and gas drilling sector but not for the geothermal drilling sector. Especially, the location of the drilling site and the costs regarding the power source are no hurdles for using electric machinery in geothermal drilling projects. This is because most geothermal projects are realized in inhabited areas where an electricity grid is available that can be tapped to power the machinery. Furthermore, the contracting bodies of geothermal projects are private persons, public agencies, or enterprises but not imperatively an oil and gas company. Hence, cheap access to diesel fuel, in most cases, is not available.[268]

By using the figures from the previously performed case study, a comparison can be made between the costs of using diesel fuel as the power source and the costs of using electricity as the power source. In the course of the case study, it is elaborated that the machinery consumes 35.769,6 kWh during the outlined project. When using diesel fuel as the power source, this energy consumption generates costs of 4.271,52€. To calculate the costs for electricity, a net price of 15,72 cents (average wholesale price) for

[268] Refer to Reuters, https://www.reuters.com/markets/commodities/oil-driller-sees-industrys-future-electric-rigs-carbon-offsets-2021-12-20/ (accessed: 18.07.2023)

a kWh is used.[269] Thus, total costs for electricity, when consuming 35.769,60 kWh, accumulate to 5.622,98€. Hence, compared to diesel, energy costs are 1.351,46€ (31,64%) higher when using electricity.

Even though the usage of electricity as the power source for drilling machinery is more expensive at first glance, it comes along with advantages. Two major advantages of an electrically driven rig are less CO_2 emissions and a considerably quieter operational noise. Both factors are crucial and can be decisive if drilling in an urban area is permitted by authorizations.[270] In addition, it should be taken into account that the price of diesel will continue to rise in the future. This is due to the rising CO_2 price.[271] Therefore, the energy costs when using diesel are approaching those costs that arise when using electricity. If the diesel price increases by 31,70% and reaches a value of 1,62€ per liter, diesel costs would be just as high as the energy costs when using electricity as a power source (assuming the electricity price remains stable).

In addition to the electrification of rigs, another alternative type of power source should at least be mentioned in the context of this Gedankenexperiment. What is meant, is the application of biofuels such as biodiesel, ethanol fuel, and biomethane as power sources for drilling machinery. These fuels are produced from biological resources like canola, soybean, oil palm, organic waste, and wood. However, the sustainability of these fuels is often disputed, since their production requires arable land, which in turn is lacking in food production. To combat this problem, the European Union has passed directives regarding sustainable energy sources and the quality of fuels ("Richtlinie über Erneuerbare Energien- RL 2009/28/EG" and "Richtlinie zur Kraftstoffqualität- RL 2009/30/EG") that include the following sustainability criteria for biofuels:

- The agricultural raw materials used for production must not come from areas with high biological diversity.
- Complete traceability of the origin of the raw materials and the biofuels produced from it must be given.
- A reduction in greenhouse gas emissions compared to fossil fuels must be given.[272]

If these criteria are met, a biofuel is classified as sustainable, and its use can reduce CO_2 emissions significantly. For example, the combustion of one liter bioethanol generates 1,504 grams of CO_2, which results in a saving in CO_2 emissions of 42,53% compared to burning diesel.[273] If the converted rig were operated with bioethanol instead of conventional diesel, around 194 tons of CO_2 emissions could be saved per year.

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[269] Refer to E-Control, https://www.e-control.at/kmu-energiepreis-check (accessed: 29.08.2023)
[270] Refer to Reuters, https://www.reuters.com/markets/commodities/oil-driller-sees-industrys-future-electric-rigs-carbon-offsets-2021-12-20/ (accessed: 18.07.2023)
[271] Refer to Wien Energie, https://positionen.wienenergie.at/wissenshub/energie-dashboard/co2-preis-in-oesterreich/ (accessed: 29.08.2023)
[272] Refer to Umweltbundesamt, https://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0360.pdf (accessed: 29.08.2023)
[273] Refer to Forrest Research, https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/carbon-emissions-of-different-fuels/ (accessed: 29.08.2023)

Admittedly, biofuels have played almost no role in the drilling industry so far. There are two key reasons for this. Firstly, biofuels are considerably more expensive than conventional diesel and secondly, engines have to be converted to run on biofuels.[274] Nevertheless, the continuous increase in the price of diesel and the ever-increasing pressure to reduce CO_2 emissions could mean that biofuels will become interesting for the drilling industry in the future.

[274] Mobile.de, https://www.mobile.de/magazin/artikel/biokraftstoff-alles-zu-pflanzenoel-biodiesel-bioethanol-und-biomethan-3710 (accessed: 29.08.2023)

3.6 Analysis of the geothermal drilling market

The last chapters had their focus on the conversion of the workover rig. In this chapter, the geothermal drilling markets of Austria and Germany are investigated and analyzed. It is of interest which players are operating in the Austrian and German drilling markets of shallow, medium-deep, and deep drilling and what kind of services and products they offer. As mentioned in Chapter 3.1.2, the converted AM12/50 is capable of drilling medium-deep wells of a maximum of 800 meters, therefore, the medium-deep drilling businesses of Austria and Germany are of special interest. That way, the competitive situation for the converted rig can be examined.

3.6.1 Introduction

Generally, geothermal drilling markets are strongly interconnected with the markets of geothermal applications. The type of geothermal application determines if drilling is necessary and, in case drilling of a well is necessary, the type of application determines the depth of the well. Since this relation is essential, another look at Austria´s and Germany´s installed capacities of the different geothermal systems is required. However, before the markets of Austria and Germany are analyzed, a brief and striking excursus is presented that explains how deep the borehole of a geothermal heat pump must be, in order to generate a certain output. This information helps to understand the composition of Austria´s and Germany´s geothermal drilling markets.

The borehole depth of a geothermal heat pump system depends on two factors. On the one hand, the depth depends on the required heating capacity, and on the other hand, it depends on the geological composition of the subsurface, hence the geothermal gradient (explained in Chapter 2.1).[275] The heating capacity of a building, in turn, depends on three factors. These are the desired room temperature, the size of the building, and its year of construction. In case the room temperature is desired to be relatively high (more than 21°C) and the building is large and relatively old (numerous decades old), the required heating capacity is relatively high. Older buildings need a higher heating capacity because their isolation is not as effective as at new buildings.[276]

Figure 52 illustrates the required heating capacities of different buildings for a room temperature of 21°C. Table 15 lists examples of how deep a geothermal well must be in order to heat a building to at least 21°C. The values presented in Table 15 are computed with the rule of thumb which indicates that 18 to 24 meters need to be drilled per kW heating capacity, depending on the geology.[277]

[275] Refer to KDS GmbH, https://www.kds.co.at/leistungen/tiefenbohrung-und-erdwaerme/ (accessed: 18.04.2023)
[276] Refer to Effizienzhaus-Online, https://www.effizienzhausonline.de/heizleistung-haus/ (accessed: 18.04.2023)
[277] Refer to KDS GmbH, https://www.kds.co.at/leistungen/tiefenbohrung-und-erdwaerme/ (accessed: 18.04.2023)

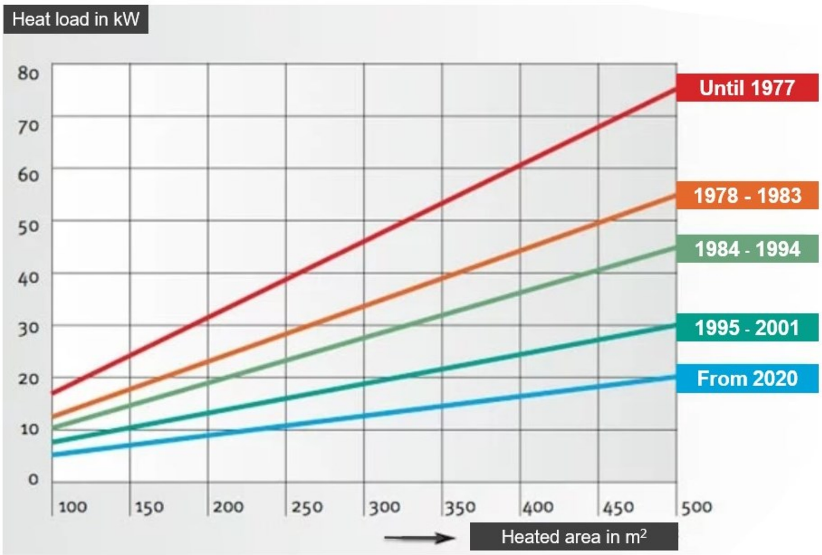

Figure 52: Heating capacity of different buildings[278]

Table 15: Heating capacities and well depth

Year of construction	Size in m^2	Required heating capacity in kW	Required well depth in meter
1960	150	24	432-576
	300	46	828-1104
	500	75	1350-1800
1980	150	18	324-432
	300	34	612-816
	500	55	990-1320
1990	150	15	270-360
	300	28	504-672
	500	45	810-1080
2000	150	11	198-264
	300	19	342-456
	500	30	540-720
2010	150	7	126-168
	300	12	216-288
	500	21	378-504

[278] Source: Effizienzhaus-Online, https://www.effizienzhaus-online.de/heizleistung-haus/ (accessed: 18.04.2023) (slightly modified)

Considering the fact that the well of a geothermal heat pump normally is only up to 200 meters deep, the required well depths presented in Table 15 seem to be problematic.

However, they are not because they do not have to be achieved by only one well. In other words, the required depth can also be realized by numerous wells. In the following, two practical examples are presented. For a private house that is to be heated by a geothermal heat pump, the drilling company drilled three boreholes of 110 meters depth. By combining the three wells into one system, sufficient heating capacity was achieved.[279]

Another reference regards a bigger project, namely the installation of a heat pump system for a production plant. In this case, the drilling company drilled 230 boreholes of 100 meters depth, hence, a total drilling depth of 23.000 meters has been accomplished. When applying the mentioned rule of thumb, this gives a heating capacity between 958 and 1.278 kW.[280] So, higher heat capacities are not necessarily linked to deeper wells but can also be achieved by multiple shallow wells. However, the multiple-well solution requires the availability of sufficient space. This is because the distance between the single wells is supposed to be a minimum of six meters. Additionally, the distance between a well and the adjacent property needs to be at least three meters.[281]

3.6.2 Austrian drilling market

In this chapter, the geothermal drilling market of Austria is analyzed. It is presented which players are active in this business and what kind of services they offer.

Quantity of installed applications

As already mentioned, the capacity of installed heat pumps in Austria is 10 times higher than the one of deep geothermal systems.[282] Currently, more than 400.000 units of heat pumps are installed in Austria.[283] However, it is necessary to distinguish between heat pumps that extract heat from ambient air, which represent the majority, and heat pumps that extract heat from the subsurface, thus being geothermal heat pumps. The number of geothermal heat pumps accumulated to around 90.000 in 2020 which meant that every third heat pump is a geothermal one. For this thesis, it is of interest to which different geothermal systems these heat pumps are connected and what their shares are. In 2017, the market share of shallow geothermal probes was 20,1%, while the market share of

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279 Refer to KDS GmbH, https://www.kds.co.at/referenzen/erdwaermebohrung-wien-penzing/ (accessed: 24.04.2023)
280 Refer to KDS GmbH, https://www.kds.co.at/referenzen/tiefenbohrungen-senica-slowakei/ (accessed: 24.04.2023)
281 Refer to Hausbaumagazin, https://www.hausbaumagazin.at/tiefenbohrungen-zur-erdwaermenutzung-kosten-und-genehmigung/ (accessed: 24.04.2023)
282 Refer to Goldbrunner, J.; Götzl, G.; (2019): Geothermal Energy Use, Country Update for Austria, page 6
283 Refer to Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation and Technologie (2022): Energie in Österreich. Zahlen, Daten, Fakten, page 23

shallow two well systems that produce from and inject into an aquifer was 3,6%. Assuming these market shares stayed relatively constant after 2017, the total number of installed units in 2020 was around 70.000 for shallow geothermal probes and around 12.500 for shallow two well systems. The rest of the 90.000 installed shallow geothermal applications in 2020, around 7.500 installations, were constituted by geothermal heat collectors.[284] Since geothermal heat collectors do not require a borehole, they are not of further interest. Consequently, it can be stated that until the year 2020, around 82.500 geothermal heat pumps have been installed that required the drilling of a borehole. However, this does not imply that exactly 82.500 shallow boreholes have been drilled since one shallow geothermal application can consist of several boreholes. Therefore, the number of shallow geothermal wells, most probably, is a multiple of the installed applications and accumulates to several hundred thousand.

As already mentioned in Chapter 2.2.3, in Austria there are also some deep geothermal projects, hence projects that include wells with depths up to a few thousand meters. In total, 77 deep geothermal wells exist in Austria. The distribution of these wells and their cumulative depths are presented in Table 16.

Table 16: Deep geothermal wells in Austria[285]

Unit	Total number of wells	Cumulative depth
Styrian Basin	28	48.600 meters
Upper Austrian Molasse Basin	14	30.828 meters
Vienna Basin and lower Austrian Molasse Basin	8	12.605 meters
Northern Calcareous Alps and Upper Austroalpine Units (mainly carbonatic)	7	14.802 meters
Lower and Upper Austroalpine Units (mainly crystalline)	19	27.483 meters
Pannonian Basin	1	860 meters
Total	77	135.178 meters

By using the figures from Table 16, it can be calculated that the average drilling depth of a deep geothermal well in Austria, which is the cumulative depth divided by the total number of wells, accumulates to around 1.756 meters. However, like the geothermal well in the Pannonian Basin, there are also some deep wells that are significantly shallower than the average depth.[286]

Summarized, the numerical distribution of the different geothermal systems and the according geothermal wells in Austria is very distinct. A six-digit number of shallow

[284] Refer to Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (2022): FTI-Roadmap Geothermie, page 14
[285] Source: Goldbrunner, J.; Götzl, G.; (2019), page 2 (slightly modified)
[286] Refer to Goldbrunner, J.; Götzl, G.; (2019), page 2

geothermal wells exists, while only 77 deep geothermal wells have been drilled so far. Understandably, this tendency also reflects in the market of Austrian drilling companies, thus, numerous Austrian companies offer the service of drilling shallow geothermal wells, while only one Austrian company offers the drilling of deep geothermal wells.

Austrian drilling companies

For the analysis of Austrian drilling companies, the register of companies provided by the Austrian Economic Chamber (Wirtschaftskammer Österreich, WKO) is utilized. By using different keywords like geothermal heat ("Erdwärme"), geothermal energy ("Geothermie"), water well builder ("Brunnenmeister"), and geothermal probe ("Erdsonden"), a list of more than 100 drilling companies is generated. From this list, the companies that only offer consulting, planning, supervision, and similar services need to be filtered out. The resulting list is compared with the list of members of the Association of Austrian drilling, well construction and foundation engineering companies ("VÖBU-Vereinigung Österreichischer Bohr-, Brunnenbau- und Spezialtiefbauunternehmungen"), in order to not miss a drilling company. Finally, it is possible to filter the companies that explicitly offer the drilling of geothermal wells. In total, these are 39 drilling companies. Table 17 presents the distribution of these companies among Austria´s states.

Table 17: Regional distribution of Austrian geothermal drilling companies

State	Number of companies
Upper Austria	14
Lower Austria	7
Tyrol	5
Styria	5
Vienna	3
Carinthia	2
Burgenland	2
Vorarlberg	1
Salzburg	0

It can be stated that companies offering geothermal drilling are distributed all over Austria (except Salzburg). Most companies are based in Upper Austria, while in Salzburg no such companies exist.[287] However, more interesting than their location is their portfolio of drilling services.

[287] Refer to WKO Firmen A-Z, https://firmen.wko.at/erdsonden/?firma=erdsonden (accessed: 24.04.2023)

Only one Austrian company exists that is able to drill deep geothermal wells of several thousand meters. This company is called RED Drilling & Service GmbH and is based in Gampern, Upper Austria. It disposes of two fully equipped drilling rigs and corresponding crews who can operate them. The rigs are capable of bearing a maximum of 300 tons of hook load, which enables them to drill to depths of up to 5.500 meters.[288] The RED Drilling & Service GmbH drilled deep hydrothermal wells for commercial geothermal projects in Munich, Simbach-Braunau, and Fürstenfeld.[289] In addition, the company performs workover jobs. For this reason, it possesses workover units of two different types which can bear maximum hook loads of 95 tons respectively 69 tons. The fitting of these units does not include drilling equipment like a rotary table or a top drive.[290]

RED Drilling & Service GmbH also offers various consulting services concerning deep drilling and the realization of hydrothermal projects.[291]

The remaining 38 companies focus on shallow geothermal drilling projects. Their scope of drilling services and, especially, their drilling machinery is relatively uniform. These companies mainly are water well builders ("Brunnenbauer") and offer the drilling of shallow geothermal wells as an additional area of business. This fact distinguishes these companies from the RED Drilling & Service GmbH which originally only drilled oil and gas wells. This difference in the original business, especially, expresses in the applied machinery. Whereas the RED Drilling & Service Company GmbH deploys conventional rotary drilling rigs, the water well builders use smaller drilling machines as introduced in Chapter 2.4.5 and shown in Figure 40a and Figure 40b.

Scope of services of Austrian water well builders

Most of the Austrian water well builders are rather small enterprises, only possess one or two drilling machines, and exclusively operate regionally. Exceptions, companies that operate supra-regional, are companies like KDS GmbH based in Grafenschachen, Burgenland, and Hagleitner Bohrtechnik GmbH & Co. KG based in Kirchberg, Tyrol. These companies dispose of several drilling machines and crews which can operate them. They conduct shallow geothermal drilling jobs all across Austria and even in neighboring countries. KDS GmbH and its references have already been mentioned when explaining how to achieve the required depth for certain heating capacities. Especially, their project in Slovakia, where they drilled 230 boreholes of 100 meters depth, indicates that this company possesses certain capacities. The duration of his project was around six months and they deployed two drilling machines and 14

[288] Refer to RED Drilling & Service Company, https://www.red-drilling-services.at/dienstleistungen/bohr-workoveranlagen.html (accessed: 25.04.2023)
[289] Refer to RED Drilling & Service Company, https://www.red-drilling-services.at/unternehmen/portrait.html (accessed 25.04.2023)
[290] Refer to RED Drilling & Service Company, https://www.red-drilling-services.at/dienstleistungen/bohr-workoveranlagen.html (accessed: 25.04.2023)
[291] Refer to RED Drilling & Service Company, https://www.red-drilling-services.at/dienstleistungen/hydrogeologie.html (accessed: 25.04.2023)

workmen.[292] However, KDS GmbH, as one of Austria´s biggest drilling company, only have drilling machines that are capable of drilling up to a depth of 200 meters.

As already mentioned above, independent of the company´s dimensions, the scope of offered drilling services is relatively uniform and, in most cases, is not just limited to the drilling of a borehole. For example, the range of services offered by KDS GmbH is presented. Basically, KDS GmbH offers a complete package, so that the heat pump can be put into operation as soon as they have completed their work. This package includes the investigation of the ground regarding its capability for a geothermal probe, the obtaining of regulatory approvals, the drilling of a borehole, the execution of a geothermal response test (GRT), the completion of the borehole, the installation of the probe, and the installation of the heat pump.[293] The scope of services of Hagleitner Bohrtechnik GmbH & Co. KG is almost the same, except they do not have an in-house plumber division and cannot offer the installation of the heat pump.[294] A service, both companies offer, is the conduction of a geothermal response test. For executing this test, an exploration well is drilled, a probe installed, and the borehole backfilled. At the surface, a GRT measurement device is attached to the probe, as shown in Figure 53.

Figure 53: Geothermal response test[295]

The purpose of a geothermal response test is to determine the heat conductivity of the subsurface. Collecting this data is important to be able to dimension the geothermal application. Concretely, the heat conductivity of the underground is a decisive parameter for the number of required wells, the distance between them, and the dimensioning of

[292] Refer to KDS GmbH, https://www.kds.co.at/referenzen/tiefenbohrungen-senica-slowakei/ (accessed: 24.04.2023)
[293] Refer to KDS GmbH, https://www.kds.co.at/leistungen/tiefenbohrung-und-erdwaerme/ (accessed: 18.04.2023)
[294] Refer to Hagleitner Bohrtechnik GmbH & Co. KG, https://www.hagleitner-bohrungen.at/erdsonden/#EWS-Anschluss (accessed: 04.05.2023)
[295] Source: Think Geo Energy, https://www.thinkgeoenergy.com/studying-the-geothermal-energy-in-brazil-interview-with-helene-hofmann/ (accessed: 03.05.2023)

the heat pump. After undertaking the GRT, the exploration well, drilled for the GRT, can be easily integrated into the geothermal application.[296] However, it needs to be stated that this type of test is only conducted when planning a heat pump application of a relatively large capacity, namely more than 30 kW.[297]

To get an idea of the costs regarding the establishment of shallow geothermal probes, several companies are contacted. In order to get an offer without engagement, it is necessary to provide information about the building that is to be equipped with a geothermal application. For this reason, it is declared that the building is located in the village of Lenzing, Upper Austria, and the required heating capacity is around 20 kW. One company, namely Hagleitner Bohrtechnik GmbH & Co. KG, delivers an offer for the establishment of five geothermal probes of which each is 90 meters deep. Hence, 450 meters are drilled in total. The offered package includes the obtaining of approvals but not the fees that have to be paid to the particular authorities. Furthermore, the offer comprises the drilling operation itself and the installation of the probes and all required connections. Table 18 presents the composition of the net charges.

Table 18: Costs of a geothermal probe system in Austria[298]

Service	Net charge
Planning and obtaining approvals	740,00€
Drilling, installation of probes, and backfilling	34.420,00€
Establishment of a shaft and installation of connections at the surface	7.377,20€
In total	**42.537,20€**

Additional to the charges registered in Table 18, the offer lists optional positions of around 7.212,50€. These positions can incur according to necessity during the operation. Examples of optional positions are the execution of geological surveys and tests or the usage of special material (for instance carbonless backfilling material) because of regulatory directives. It can be stated that, from the client´s point of view, the net price per meter drilled is between 94,53€ and 110,55€, depending on the optional services that are required.[299]

Summary

When summarizing the analysis of the Austrian drilling market, there is no company in Austria that offers the drilling of medium-deep boreholes. On the one hand, there are the conventional water well builders whose machinery is not capable of drilling deeper than 200 meters, on the other hand, there is the RED Drilling & Service GmbH whose rigs are

[296] Refer to KDS GmbH (2022): TRT- Test
[297] Refer to Hagleitner Bohrtechnik GmbH & Co. KG, https://www.hagleitner-bohrungen.at/erdsonden/#EWS-Anschluss (accessed: 04.05.2023)
[298] Source: Hagleitner Bohrtechnik GmbH & Co. KG (2023): Angebot (slightly modified)
[299] Refer to Hagleitner Bohrtechnik GmnH & Co. KG (2023): Angebot

dimensioned for deep drilling. The application of deep drilling rigs for medium-deep geothermal projects, because of financial reasons, is not common. Operating big drilling rigs is very cost-intensive because of high energy costs and high personnel costs.

3.6.3 German drilling market

The German drilling market with all its players, and their offered services, are in the center of this chapter. First, the installed capacities of geothermal applications in Germany need to be examined, since the composition of the drilling market can be derived from that.

Quantity of installed applications

The installed capacity of shallow geothermal applications, which is the capacity of geothermal heat pumps, is 10 times higher than the capacity of deep geothermal applications. According to the “Bundesverband Geothermie”, currently, 470.000 geothermal heat pump applications with a total capacity of 4.700 MW are installed in Germany. Around 10% of these applications, so ca. 47.000 units, are shallow two well systems, hence produce from and inject into an aquifer. The remaining 423.000 applications either comprise geothermal probes or heat collectors. Since heat collectors do not include boreholes, they are of no further interest in this context. Unfortunately, it is not possible to identify an exact value of the heat collector´s share but the “Fraunhofer Institute” states that the majority of these 423.000 units gain temperatures via probes, therefore, include boreholes.[300] Considering the fact that shallow two well systems consist of two boreholes in any case and also many geothermal probe applications consist of more than one borehole, it can be estimated that Germany´s total number of shallow geothermal wells is a high six-digit value or even above one million.

The “Bundesverband Geothermie” lists Germany´s deep geothermal systems, however, does not provide information about the number of deep geothermal wells. By early 2023, 42 deep geothermal power plants were operating in Germany, while 14 more plants were under construction and a further 82 plants were planned. More than half of the operating plants are located in Bavaria, while the remaining plants are distributed over the states of Baden-Würtemberg, Berlin, Brandenburg, Mecklenburg-West Pomerania, North Rhine-Westphalia, Rhineland-Palatinate, and Saxony. The majority, namely 34 out of the 42 operating plants, are hydrothermal plants, hence, comprise a minimum of one injection and one production well. Also, the plants under construction are mainly hydrothermal systems. Well depths of existing hydrothermal power plants vary between 825 meters and 5.078 meters. However, more than half of hydrothermal wells are deeper than 2.000 meters. The remaining eight operating deep geothermal plants are either deep geothermal probes or plants that make use of mining water. The latter-mentioned

[300] Refer to Fraunhofer-Einrichtung für Energieinfrastrukturen und Geothermie IEG (2022): Roadmap Oberflächennahe Geothermie, page 15

plants utilize the infrastructure of former coal mines that are flooded with mining water. In Germany, there are three plants of this type that produce mining water from depths of 570 meters, 628 meters, respectively 1.200 meters. Germany´s four deep geothermal probes are installed in wells of 700 meters, 773 meters, 800 meters, and 2.835 meters depth.[301]

Not only Germany´s geothermal power plants include deep wells, but also hot spring resorts. In total, there are 168 hot spring resorts in Germany, that produce from deep geothermal reservoirs.[302] To get an idea of how deep the wells of these geothermal applications are, the 1.650 meters deep well of the thermal resort Templin, Brandenburg, can be presented as an example.[303] Another example is the well of the Jordanbad, Baden-Würtemberg, with a depth of 1.000 meters.[304]

By knowing the number of deep geothermal systems, the number of deep geothermal wells can be estimated to be a few hundred. Compared to the number of shallow geothermal wells, it can be stated that the numerical distribution of the different geothermal systems is very clear. Like in Austria, this tendency can also be found in the market of German drilling companies, which is dominated by companies offering shallow drilling services.

German drilling companies

Generally, the analysis of Germany´s drilling landscape is more difficult to conduct than the analysis of the Austrian one. On the one hand, this has to do with its bigger dimension, on the other hand, this is because no comprehensive information platform as Austria´s "Firmen A-Z" by the Austrian Economic Chamber exists. Indeed, a business register ("Unternehmensregister") exists that registers all German companies, nevertheless, it is not possible to recall a list of companies in a certain industry. Therefore, the Central Association of the German Construction Industry ("Zentralverband Deutsches Baugewerbe") was contacted for providing information about German companies operating in the drilling business, especially, in the geothermal drilling business. Unfortunately, this institution cannot tell the exact number of companies operating in the business of shallow, respectively deep geothermal drilling. However, they provide a document regarding selected figures of the construction industry ("Ausgewählte Zahlen für die Bauwirtschaft“) composed by Germany´s federal office of statistics („Statistisches Bundesamt“). This document helps to get an idea of the shallow geothermal drilling market since it can be learned, that at the end of 2022, 701 German companies offered services in the field of water well building. Only companies that employ more than 20 people are included in this statistic, thus smaller companies are not considered.[305] Certainly, this number of companies is restricted in its expressiveness,

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301 Refer to Bundesverband Geothermie (2023): Tiefe Geothermieprojekte in Deutschland-Projekte in Betrieb, page 1 p.
302 Refer to Bundesverband Geothermie, https://www.geothermie.de/geothermie/geothermie-in-zahlen.html, (accessed: 07.03.2023)
303 Refer to Naturtherme Templin, https://www.naturthermetemplin.de/bad/thermalsole (accessed 08.05.2023)
304 Refer to Jordanbad, https://www.jordanbad.com/therme/ (accessed: 08.05.2023)
305 Refer to Statistisches Bundesamt (2023): Ausgewählte Zahlen für die Bauwirtschaft, page 78

because it not only includes companies that provide drilling services but also companies that only provide planning and projecting services. An additional restricting impact is the fact that not all water wall builders offer the drilling of geothermal wells. Consequently, the number 701 needs to be corrected to obtain the number of water well builders operating in the shallow geothermal drilling business. Nevertheless, it can be assumed, that a few hundred such companies exist in Germany.

Scope of services of German water well builders

To get a picture of the offered services of German water well builders, at least one random sample in each German state was examined. Only in the state of Bremen, no water well builder, offering the drilling of geothermal wells, was found. When examining the companies, the focus was especially on their offered drilling depth and their applied machinery. In Appendix B, the complete list of the investigated companies can be found.

In large parts, the range of geothermal services of the examined companies is similar to the range of geothermal services of Austrian water well builders. Mainly, the establishment of shallow two well systems or shallow geothermal probes is offered. The machinery applied for these purposes are capable of drilling to maximum depths of 100 to 200 meters. However, some companies are discovered that dispose of drilling machinery that can drill medium-deep to deep boreholes. These exceptions are the following. Handke Brunnenbohr GmbH possesses a DSB5/50 drilling rig (mentioned in Chapter 2.4.8), which they upgraded in 2023 from 50 tons of hook load to 65 tons of hook load. Before that upgrade, in 2014, they drilled a 1.500 meter deep geothermal well in Kaiserslautern, Germany. With the upgraded hook load, the rig can bear longer drill strings, hence, can drill even deeper boreholes.[306] The company H. Pettenpohl Tiefbohrges. mbH offers the drilling of boreholes for thermal waters up to depths of 1.000 meters.[307] Ivers Brunnenbau GmbH disposes of machinery and qualifications to drill 500 meters deep geothermal wells.[308] The last randomly examined company that is capable of drilling medium-deep geothermal wells is the company Erdbohrtechnik Brüntjen GmbH. This company is capable of drilling to a maximum depth of 400 meters.[309]

The random examination of water well builders offering the drilling of geothermal wells can be summarized by stating that the vast majority focuses on the drilling of shallow wells, whereas only a little fraction is able to drill medium-deep or even deep geothermal wells. This tendency can also be confirmed by experts, which state that few German water well builders have the possibilities and machinery to drill into medium-deep and deep reservoirs. Examples for such companies are Abt Wasser- und Umwelttechnik GmbH and Ochs Bohrgesellschaft mbH.[310] Abt Wasser- und Umwelttechnik GmbH

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306 Refer to Handke Brunnenbau GmbH, https://www.handke-brunnenbau.de/unternehmen/ (accessed: 11.05.2023)

307 Refer to H. Pettenpohl Tiefbohrges. mbH, https://www.brunnensanierung.de/#unternehmen (accessed: 11.05.2023)

308 Refer to Ivers Brunnebau GmbH, https://www.ivers-brunnenbau.de/erdwaerme/ (accessed: 09.05.2023)

309 Refer to Bohrtechnik Brüntjen GmbH, https://erdbohren.de/ (accessed: 11.05.2023)

310 Uhlig, S.; (08.05.2023): personal communication

declares on their homepage that they can drill up to 1.500 meters in depth.[311] Ochs Bohrgesellschaft mbH, on the other side, states on its homepage that it can establish boreholes with depths of around 1.000 meters.[312]

It can be concluded that in Germany there are water well builders, although a small number, which are offering geothermal drilling services up to depths of 1.500 meters. This fact distinguishes the German water well builder market from the Austrian one. In Austria, the water well builders exclusively focus on the drilling of shallow boreholes of a maximum of 300 meters deep.

To get an idea of what the establishment of a shallow geothermal probe in Germany costs, a publication of a German advisor for energy regarding building and living is consulted. It states that the establishment of a shallow geothermal probe costs between 50€ and 100€ per meter drilled and strongly depends on on-site conditions and geology. These presented costs include the drilling, the installation of the probe, and the backfilling of the borehole.[313] Table 19 presents the composition of all net charges.

Table 19: Costs of a geothermal probe system in Germany[314]

Service	Net charges
Obtaining of approvals	250€-600€
Establishment of site facilities	300€-750€
Drilling, installation of probes, and backfilling	50€-100€ per meter
Shaft and connections at the surface	1.000€-1.250€
Removal or redistribution of cuttings	400€-550€
In total (for 450m depth)	**24.450€ (cheapest)** **36.300€ (average)** **48.150€ (most expensive)**

When calculating with average values for a total depth of 450 meters (the same depth as in the offer of Hagleitner Bohrtechnik GmbH & Co. KG), the total costs accumulate to 36.300€. This gives a price per meter drilled of around 81€. When calculating with the highest possible charges, the sum is 48.150€ (107€ per meter drilled), and when calculating with the lowest possible charges, the sum is 24.450€ (54,33€ per meter drilled). These values help to get an idea about the costs of a shallow geothermal probe in Germany. To get concrete numbers, an offer from a German contractor needs to be

[311] Abt Wasser- und Umwelttechnik GmbH, https://abt-wut.de/brunnenbau/ (accessed: 11.05.2023)

[312] Ochs Bohrgesellschaft mbH, https://ochs-bau.de/brunnenbau/brunnenbau-leistungen (accessed: 11.05.2023)

[313] Refer to Grünes Haus, https://gruenes.haus/erdwaerme-tiefenbohrung/ (accessed: 11.05.2023)

[314] Source: Grünes Haus, https://gruenes.haus/erdwaerme-tiefenbohrung/ (accessed: 11.05.2023) (slightly modified)

solicited. Because German contractors demand detailed information of the property to be drilled, this is not possible in the course of this thesis.

German deep drilling companies

After investigating Germany´s market of water well builders, the landscape of Germany´s deep drilling companies is discussed subsequently. During the market analysis, six German companies are identified as deep drilling companies. At this point, it needs to be stated, that not only German companies drill deep geothermal wells in Germany but also companies from abroad. The foreign companies that operate in Germany are the RED Drilling & Service GmbH and the Huisman Equipment B.V..[315] The German deep drilling companies are briefly introduced in the following passages. Namely, these are DrillTec GUT GmbH, KCA Deutag Drilling GmbH, MB Well Services GmbH, H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH, Daldrup & Söhne AG, and Zübling Spezialtiefbau GmbH.

- DrillTec GUT GmbH is based in Deggendorf, Bavaria, and offers end-to-end project handling of drilling a deep geothermal well. Besides the drilling itself, this includes planning, analysis, obtaining approvals, documentation, and coordination among other tasks.[316] They possess two types of drilling rigs which are capable of drilling 3.500 meters, respectively 5.000 meters deep. As a rotary source, these rigs are equipped with top drives. Their power, they derive either from engines and generators, or they are connected to the electricity grid. Additionally, these rigs are fitted with so-called skidding systems.[317] DrillTec Gut GmbH deploys these rigs for deep drilling projects in Germany but also in the neighboring countries.[318] A skidding system consists of a skidding track over which the rig can be moved as a whole for a short distance. Especially, for hydrothermal deep drilling this is very useful because an injection and a production well need to be established. On the surface, these wells are only a few meters away from each other. With the help of a skidding system, the drilling rig can be moved over that distance and does not have to be dissembled.[319]
- KCA Deutag Drilling GmbH is based in Bad Bentheim, Lower Saxony, and is a subsidiary of the Scottish KCA Deutag Group. They offer an end-to-end project handling and dispose of four different types of onshore drilling rigs. These rigs have theoretical drilling depths of 7.400 meters (480t hook load), 7.000 meters (509t hook load), 5.486 meters (420t hook load), and 5.000 meters (350t hook load). Their rotation can either be actuated by a rotary table or a top drive.[320]

[315] Refer to Forstner, I.; (2023), E-Mail
[316] Refer to DrillTec GUT GmbH, https://www.drilltec.de/geschaeftsfelder/tiefbohrungen/einsatzgebiete (accessed: 15.05.2023)
[317] Refer to DrillTec GUT GmbH, https://www.drilltec.de/bohranlagen/tiefbohranlagen (accessed: 15.05.2023)
[318] Refer to DrillTec GUT GmbH, https://www.drilltec.de/geschaeftsfelder/tiefbohrungen/referenzen (accessed: 15.05.2023)
[319] Refer to Mammoet, https://www.mammoet.com/equipment/special-equipment/skidding-systems/skidding-system/ (accessed: 15.05.2023)
[320] Refer to KCA Deutag Drilling GmbH, https://www.kcadeutag.com/rig-fleet (accessed: 15.05.2023)

- MB Well Services GmbH is located in Salzwedel, Saxony-Anhalt, and offers, as all the other five companies, complete project handling. The rig fleet comprises eight different types of drilling rigs respectively heavy workover rigs. The maximum hook load of their most powerful rig in this regard accumulates to 220 tons. The specified maximum drilling depth that can be realized by this company is 3.500 meters.[321]
- H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH is based in Hessisch Lichtenau, Hesse, and has its origins in conventional water well construction. Only in the last 15 years, this company has developed into the deep drilling business. Today, H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH offers end-to-end settlement of shallow, medium-deep, and deep drilling projects.[322] For shallow and medium-deep projects they have a drilling machine fleet consisting of seven different types. The most powerful drilling machine (maximum hook load of around 60 tons) can drill to around 2.200 meters depth, even though, this depth can only be achieved by core drilling, hence, only with a very small diameter of around 10 centimeters. A diameter of around 18 millimeters, which is typical for a geothermal probe, can be drilled to a depth of 1.000 meters with this machine.[323] For deep drilling purposes, 3 different types of drilling rigs are available. These rigs can drill to depths of around 5.000 meters (maximum hook load of around 410 tons), 2.500 meters (maximum hook load of around 120 tons), and 1.000 meters (maximum hook load of around 70 tons).[324] So, it can be stated, that H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH disposes of drilling machines and rigs that cover any drilling depths up to 5.000 meters.
- Daldrup & Söhne AG is based in Ascheberg, Nordrhine-Westphalia, and offers an equal range of services than H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH. This company operates in the shallow to medium-deep drilling business, as well as in the deep drilling business.[325] In total, they possess 41 drilling rigs and machines. However, 24 of these units are small dimensioned drilling machines with hook loads between 0,75 tons and 12 tons. The most powerful of these units can drill to depths of a maximum of 200 meters. For drilling depths between 200 meters and 1.000 meters, Daldrup & Söhne AG dispose of 12 drilling machines with hook loads between 16 tons and 46 tons. Five drilling rigs of their fleet are capable of drilling deep wells. Their hook loads vary between 70 tons and 350 tons, whereas they are designed to have a rather small footprint. A small footprint, in this context, means that they require as little space as possible and produce as little emissions (mainly exhaust and noise) as possible. These drilling rigs have maximum drilling depths of 2.000/2.800/3.000/4.000/6.000 meters each.[326]

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[321] Refer to MB Well Services GmbH, https://www.mbwellservices.com/service/geothermie/ (accessed: 15.05.2023)
[322] Refer to H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH, https://angers-soehne.com/leistungen/ (accessed: 15.05.2023)
[323] Refer to H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH, https://angers-soehne.com/leistungen/geraete-oberflaechennahe-bohrungen/ (accessed: 15.05.2023)
[324] Refer to H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH https://angers-soehne.com/leistungen/geraete-tiefbohrungen/has-b4/ (accessed: 15.05.2023)
[325] Refer to Daldrup & Söhne AG, https://daldrup.eu/de/?id_seite=35 (accessed: 15.05.2023)
[326] Refer to Daldrup & Söhne AG, Gerätepark (w.rd.)

- Zübling Spezialtiefbau GmbH is based in Stuttgart, Baden-Württemberg, and belongs to the Strabag Group. Zübling Spezialtiefbau GmbH has an Austrian subsidiary called Züblin Spezialtiefbau Ges.m.b.H., however, this subsidiary does not dispose of drilling equipment.[327] Zübling Spezialtiefbau GmbH offers complete project handling concerning medium-deep (1.000 to 1.500 meters) to deep (up to 5.000 meters) geothermal drilling.[328] As a reference, the deep geothermal drilling project in Mehrnbach, Upper Austria, can be listed. In the course of this project, a 2.610 meters deep well was drilled by Zübling Spezialtiefbau GmbH from November 2018 until February 2019.[329]

Summarized, three of these six drilling companies not only offer deep drilling jobs but also medium-deep drilling jobs. Especially, H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH and Daldrup & Söhne AG are standing out because they have drilling machinery at their disposal, which is capable of drilling shallow, medium-deep, and deep geothermal wells.

3.6.4 Comparison of the Austrian and German drilling market

Due to the difference in size between the two countries, the German drilling market is of course much larger than the Austrian one. There are significantly more German drilling companies than Austrian ones, although the distribution of their specialist areas is almost identical in both countries. In Austria as well as in Germany there are far more shallow drilling companies, so water well builders, than deep drilling companies. In Austria, there is only one company that can drill deep wells, while in Germany there are a total of six companies that can drill deep wells. In contrast, 38 Austrian and several hundred German companies offer the drilling of shallow geothermal wells. When it comes to the scope of services of these companies, there are almost no differences between the two countries. Whether the costs for the customer of a shallow geothermal probe are identical across the two countries, is shown in Table 20.

[327] Refer to Züblin Spezialtiefbau GmbH, https://www.zueblin-spezialtiefbau.de/databases/internet/_public/content30.nsf/web30?Openagent&id=751E28154AF18ACDC12582AC003E02BD&men1=2&men2=undefined&sid=200 (accessed: 15.05.2023)
[328] Refer to Züblin Spezialtiefbau GmbH, https://www.zueblin-spezialtiefbau.de/databases/internet/_public/content30.nsf/web30?Openagent&id=B5BBA5C20E253DEAC1258964003635A7&men1=4&men2=undefined&sid=406 (accessed: 15.05.2023)
[329] Refer to Züblin Spezialtiefbau GmbH, https://www.zueblin-spezialtiefbau.de/databases/internet/_public/content30.nsf/web30?Openagent&id=B1F6ECAADCB4F836C12584F700377915#?men1=4&men2=undefined&sid=406 (accessed: 15.05.2023)

Table 20: Comparison of a shallow geothermal probe´s costs[330] [331]

Service	**Costs in Austria**	**Costs in Germany**
Planning and obtaining approvals	740,00€	250,00€-600,00€
Establishment of site facilities	34.420,00€	300,00€-750,00€
Drilling, installation of probes, and backfilling		50,00€-100,00€ per meter drilled
Removal or distribution of cuttings		400,00€-550,00€
Establishment of a shaft and installation of connections at the surface	7.377,20€	1.000,00€-1.250,00€
Sub-total	42.537,20€	
Optional positions	7.212,50€	
Total	**49.749,70€**	**24.450,00€ (cheapest)** **36.300,00€ (average)** **48.150,00€ (most expensive)**

It is vital to mention that for the purpose of that comparison, an actual offer from a contractor and guiding values from an advisor are opposed. Above all, the relatively imprecise information provided by the advisor makes a meaningful comparison difficult. To make a comparison as precise as possible, it is assumed that the job is relatively complicated, and the costs are as high as possible. In this case, the costs in Austria and Germany are of similar quantities. Expressed in numbers, the establishment of the probe costs 49.749,70€ (110,55€ per meter drilled) in Austria and 48.150,00€ (107,00€ per meter drilled) in Germany. Hence, drilling in Austria is only 1599,70€ (3,55€ per meter drilled) more expensive. Expressed as a percentage, the costs in Austria are 3.32% higher. Thus, it can be stated that the costs of a shallow geothermal probe do not differ significantly between the two countries.

However, as already mentioned at the beginning of Chapter 3.6, the greatest interest in the context of this thesis is on the medium-deep market, and there are certainly differences between the two countries. In contrast to Germany, there is not a single company in Austria that offers medium-deep drilling. In Germany, there are water well builders (for example Abt Wasser- und Umwelttechnik GmbH and Ochs Bohrgesellschaft mbH.) that possess machinery for medium-deep drilling jobs as well as deep drilling companies that offer medium-deep drilling services. Unfortunately, it was not possible within the scope of this work to identify the exact number of German water well builders

330 Source: Hagleitner Bohrtechnik GmbH & Co. KG (2023): Angebot (slightly modified)
331 Source: Grünes Haus, https://gruenes.haus/erdwaerme-tiefenbohrung/ (accessed: 11.05.2023) (slightly modified)

that offer medium-deep drilling services. German deep drilling companies that offer medium-deep drilling services are MB Well Services GmbH, H. Anger´s Söhne Bohr- und Brunnenbaugesellschaft mbH, Daldrup & Söhne AG, and Zübling Spezialtiefbau Gmbh.

3.7 Characteristics and potential of medium-deep drilling

The primary purpose of the market analysis conducted in Chapter 3.6 was to find out which players are active in the medium-deep drilling market of Austria and Germany. The reason why the focus of the analysis is on the medium-deep drilling market is that the converted rig would fit into this market. The analysis shows that no Austrian company offers medium-deep drilling jobs, while in Germany, few companies offer medium-deep drilling jobs. Basically, the drilling market in Austria and Germany can mainly be divided into a deep drilling sector and a shallow drilling sector. This is no coincidence because the medium-deep drilling market comes along with problematic characteristics in two different regards. On the one hand, it is more difficult to identify geothermal applications for medium-deep wells than for shallow wells or deep wells. On the other hand, the drilling process of medium-deep wells holds complexities.[332]

First, the problems regarding the application of medium-deep wells are discussed. What differentiates medium-deep wells from shallow wells and deep wells is the unambiguousness regarding the installed application. Shallow geothermal applications in Austria and Germany require the installation of a heat pump because the produced temperatures are insufficient for heating purposes. The installed applications can either be heat collectors, geothermal probes, or shallow two well systems and, normally, do not exceed the depth of 200 meters. The establishment is relatively straightforward and is mainly executed by water well builders.

On the contrary, deep geothermal wells in Austria and Germany are exclusively applied for the installation of deep two well or multi-well systems. This is because the energy output of a two well or multi-well system, where hot thermal water is produced, is significantly higher than the energy output of a closed system of the same depth. As presented in Chapters 2.2.3 and 2.2.4, these systems produce thermal waters with sufficient temperatures to generate electricity or to supply a district heating network. Compared to shallow drilling projects, not only the drilling process, in this case, is much more complex, but before drilling, also cost-intensive and time-consuming exploration of the possible reservoir is necessary. By exploring the subsurface as accurately as possible, the risk of not finding the expected geothermal resources is supposed to be minimized. In total, the prearrangements and the drilling of a deep well system generate major costs. However, the fact that such projects are realized all over the world shows that clients are willing to pay these costs because of the high energy output and the high profitability of deep geothermal projects. Medium-deep reservoirs in Austria and Germany have a rather low energy content. Thermal waters in medium depths up to 600 meters, reach maximum temperatures of 40°C. For instance, in the Vienna Basin the subsurface temperature is calculated by summating an average surface temperature of 12°C and a geothermal gradient of 29°C per kilometer depth. Hence, thermal waters in the Vienna Basin at a depth of 600 meters have temperatures of 29,4°C. Thermal waters of such temperatures cannot be used for generating electricity or supplying district

[332] Refer to Uhlig, S.; (2023), personal communication

heating networks.[333] A possible application of thermal waters with temperatures of around 30°C is the infeed into a floor heating system.[334] Besides the temperature, also permeability is a critical parameter for thermal water reservoirs. The higher the permeability of the reservoir, the more volume of water can be produced in a certain period of time, hence the higher the energy output is. The typical flow rates of deep geothermal systems are 100 liters per second and more. In general, medium-deep thermal reservoirs in Austria and Germany do not possess permeabilities that allow such flow rates. This implies that medium-deep thermal projects also have lower profitability compared to deep geothermal projects. Therefore, it is not efficient to perform cost-intensive and time-consuming exploration methods to identify potential medium-deep thermal reservoirs. Consequently, there is a lack of geological data and field mapping data regarding medium-deep zones, while for deeper zones, a considerable amount of data exists. This lack of data results in a relatively high risk of not finding what is expected, namely a potential thermal reservoir. This difficulty and the relatively low energy output are the reasons why no designated market for medium-deep thermal systems has been established yet. Even though, there might be regions in Austria and Germany, where the production of thermal water out of a medium-deep reservoir is possible for low-temperature applications like floor heating systems.

In contrary to the rather problematic medium-deep thermal systems, medium-deep geothermal probes are auspicious systems. Simply, because the major obstacle of the risk of discovery plays no role. Compared to duplet or multi-well systems, probes have the big advantage of being independent of thermal water reservoirs. Hence, cost-intensive and time-consuming exploration to identify potential reservoirs is not necessary. The decisive parameters for the probe´s efficiency are the heat flux density of the subsurface, the geothermal gradient, and the probe´s depth. The higher the heat flux density is, the more heat the subsurface can transfer to the fluid within the probe. The deeper the probe and the higher the geothermal gradient, the higher the temperature to which the fluid is exposed. Basically, it can be stated that medium-deep geothermal probes have the potential to be comprehensively installed in Austria and Germany. Whereat, their installation is more efficient in some regions than in others, depending on the local heat flux density and the local geothermal gradient.[335] However, the chance of comprehensive installation does not respond to the question of possible applications. Medium-deep geothermal probes, definitely deliver higher temperatures, hence more energy, than shallow geothermal probes, but its establishment is also linked with higher CAPEX. Due to these reasons, the application of medium-deep probes for heating purposes at private houses can be excluded almost entirely. A more interesting possible field of application is the heating of, for instance, public buildings, small residential areas, or rowhouses, thus larger spaces. In this context, municipalities, energy communities, or similar can be envisaged as target groups.[336]

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333 Refer to Misch, D.; (2023), personal communication
334 Refer to Heizsparer, https://www.heizsparer.de/heizung/heizkorper/fussbodenheizung/fussbodenheizung-vorlauftemperatur (accessed: 07.06.2023)
335 Refer to Misch, D.; (2023), personal communication
336 Refer to Uhlig, S.; (2023), personal communication

As already mentioned, besides the complexity of identifying applications for medium-deep wells, their establishment, hence the drilling process, also includes special aspects that need to be considered. Especially, when it comes to the use of well control systems, which are a crucial factor during drilling, there is room for maneuvering in the medium-deep drilling sector. This fact differentiates medium-deep drilling from shallow drilling and deep drilling, in which the approach concerning well control is relatively clear and consistent among different projects. When drilling shallow wells, in almost all cases, no well control equipment is used, while for deep drilling wells, well control systems are always applied to prevent kicks and blowouts.

De jure, there are no precise guidelines from which drilling depth onward well control equipment needs to be applied in Austria and Germany. However, the legislation in force in Austria ("Bohrlochbergbauverordnung") as well as Germany (for instance the "Bergverordnung für Tiefbohrungen" of the state of Lower Saxony) clearly states which functions well control equipment needs to fulfill and how it needs to be applied. Additionally, the legislation states how a well needs to be completed (installation of casings and cementing of the annulus between casings and formation), thus no communication between different zones and no communication between the subsurface and the surface can take place.

Also, these guidelines are not coupled to a certain depth. In case the drilling depth exceeds 300 meters in Austria and 100 meters in Germany, the mining authority needs to be informed. The mining authority then decides if a plan regarding well control and well integrity needs to be elaborated by the drilling company.[337] If well control equipment needs to be applied during drilling and, if casings and cement need to be inserted into the borehole, mainly depends on the location of drilling. In case it is possible to encounter oil and gas reservoirs or overpressure formations during drilling, the authority certainly orders the application of well control equipment. In case different formations or even aquifers are drilled through, the authority certainly orders the installation of casings and cement. Since overpressure zones are very rare in shallow depths and shallow gas reservoirs are well mapped, well control equipment is hardly ever used when drilling shallow wells.[338]

Concerning well integrity, it is common practice to only fill shallow wells with cement but set no casings. Deep wells always are completed with casings and cement. For medium-deep wells it is impossible to generally state, if the application of well control equipment is necessary and, if the well needs to be fitted with casings and cement. In this regard, considerable differences among medium-deep drilling projects can occur. On the one hand, the application of well control equipment and the completion of the well with casings and cement generates significant extra costs. On the other hand, when committing to this extra effort, much more projects can be realized, for which otherwise no permission would have been granted by authorities. Therefore, every medium-deep project needs to be regarded separately, to evaluate if it is economically feasible.[339]

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[337] Refer to Spörker, T.; (2023), personal communication
[338] Refer to Misch, D.; (2023), personal communication
[339] Refer to Uhlig, S.; (2023), personal communication

4 Conclusion

In the course of the theoretical and practical part of this thesis, critical aspects concerning the conversion of an oil and gas workover rig into a drillable rig for geothermal purposes were examined. With the findings, it is now possible to make a statement regarding the question, whether the conversion is a reasonable and auspicious undertaking or not. Generally, it can be anticipated that the application of oil and gas equipment for geothermal purposes, absolutely, makes sense, even though, this statement only is appropriate for Austria and Germany. This is because the development of geothermal energy in Austria and Germany is on the rise. When believing the plans of the governments of these countries, geothermal energy is supposed to be developed extensively in the next few years. Key reasons for geothermal energy´s upswing in these countries are the intention to establish a more sustainable energy and heat supply mix and the intention to obtain more independence in regard to energy supply. As a consequence of the transition towards more sustainable energy sources, the production of oil and gas is retrogressive. In other words, the oil and gas industry in central Europe is facing a very tough and challenging future. Oil and gas companies are under pressure, thus, are obliged to make strategic decisions. The effort of applying oil and gas equipment for geothermal purposes is a strategy that meets the ravages of time. This is because the central European geothermal drilling industry urgently needs machinery, labor, and know-how to be able to realize the ambitious plans of the European Union and national governments.

When considering this general development, the question arises, if it is profitable to convert the oil and gas workover rig AM12/50 into a drilling rig, configured for medium-deep geothermal projects. Basically, this question consists of two components.

- Is the conversion of the AM12/50 economically feasible?
- Is there a target market for the services of the converted AM12/50 rig?

It is crucial to separately examine these two questions. This is because the conversion process may be financially reasonable but there is no demand for the rig´s services and vice versa.

The reply to the first question is relatively straightforward. Converting the AM12/50, definitely, makes sense from an economic point of view. The reason is that the rig itself, namely the AM12/50, already is owned by the company and the rig is by far the most expensive element among drilling equipment. As expressed in Table 9, the accumulated purchase costs of all equipment required for a medium-deep drilling project account for 3.082.489€. Since the rig with purchase costs of 1.350.000€ and other equipment with overall purchase costs of 200.000€ are already possessed by the company, an additional investment of 1.532.489€ is necessary. This means, CMB Well Services S.R.L.´s investment into a drilling rig, capable of drilling medium-deep boreholes, is only half of the investment a company needs to make when starting from scratch. In practice, the investment into additionally required equipment can be lowered by purchasing certain pieces of equipment secondhand. In the case of purchasing secondhand equipment, it is crucial to pay attention to its condition and smooth functionality so that no higher OPEX generated when applying it. Particularly, by buying expensive and long-lasting equipment like the mud pump, the mud tanks, the shale shaker, or the rotary table secondhand, several hundred thousand Euros can be saved. Since the conversion of the AM12/50 into a drilling rig is a pilot project, linked with a few technical uncertainties, the acquisition of secondhand equipment is highly recommended. That way, the investment can be approximately lowered to around 1.000.000€ (saving of 34,75%).

To make a statement regarding the economic feasibility of the conversion, several KPIs have been computed. These calculations have been conducted based on the assumption that the drilling rig is used to its full capacity, hence, realizes 50 medium-deep projects in a year´s time. This assumption has been made, because it facilitates various calculations, especially, the calculation of computed costs. In this case, the converted AM12/50 generates an annual net profit of 675.965,50€ when declarable in Austria, and 707.095,50€ when declarable in Germany. To put the CAPEX in relation to the profit, the ROI and the payback period have been calculated. The ROI accounts for 44,11% when being declarable in Austria and 46,14% when being declarable in Germany. These values are rather high and demonstrate that the conversion project can be highly profitable. The payback period of the conversion investment constitutes to 1 year and six months, which is comparatively, very short, thus, also points out the high potential of the investment.

Admittedly, the presented figures need some corrections to be more realistic. This is simply because the assumption concerning the annual project quantity of 50 is very optimistic. However, when making the realistic assumption that the rig realizes 35 one-week projects per annum, the investment still can be assessed as lucrative. For this calculation, a further assumption needs to be made, namely that the crew and the rig are used for other purposes when not drilling medium-deep geothermal boreholes. That way, the costs that accrue during that time are assigned to other projects and do not have to be considered in these calculations. In this case, the annual profit would amount to 473.175,85€ (Austria) respectively 494.966,85€ (Germany). The corresponding ROIs would account for 30,88% respectively 32,30% and the corresponding payback period would last for one year and 11 months.[340] Since these KPI values can still be considered above average, it can be concluded that the conversion of the AM12/50 has the potential of being a very profitable undertaking.

The second part of the question, namely the question of a suitable market for the medium-deep drilling services of the converted AM12/50 needs to be replied to. At the moment, most drilling companies are specialized in either shallow drilling up to a depth of 300 meters or are specialized in deep drilling starting from a depth of around 1.000 meters. In Austria no company offers medium-deep drilling services, while in Germany there is a small number of companies in this market segment. The reason for this is, that in the past there was hardly any demand for medium-deep wells in Austria and Germany. This is because the drilling of medium-deep wells holds complexities, as has been explained in Chapter 3.7. On the one hand, the drilling process of medium-deep

[340] Calculations in Appendix E

boreholes requires adequate know-how and equipment, especially, regarding well control and well integrity. On the other hand, it is difficult to offer attractive application possibilities for medium-deep boreholes. These circumstances are huge hurdles that detain many drilling companies from entering the medium-deep drilling business. In the case of the converted AM12/50, the requirement of special know-how and equipment is no obstacle, on the contrary, this is a chance to stand out from the competition. To be able to offer medium-deep drilling services including the application of well control equipment and the installation of casings is a stand-out quality characteristic that opens completely new doors. By applying well control equipment and by setting casings, authorities grant drilling projects which otherwise would not be granted. However, this is only a competitive advantage if it does not cause drilling costs to explode. The medium-deep geothermal probe must represent an attractive product for the customer which must be able to assert itself, particularly, against the strong and cheaper competition of shallow geothermal probes.

As calculated in Chapter 3.2, the establishment of a 700m deep geothermal probe by the AM12/50 causes the customer net costs in the amount of 136.379,08€. Not yet included in these costs is the establishment of the well´s conductor and different minor tasks on the surface like the establishment of a central shaft. Hence, the total costs of the geothermal probe´s establishment are even higher. When only considering the computed costs of 136.379,08€, one meter drilled generates costs for the customer of around 194,83€. For comparison, Hagleitner Bohrtechnik GmbH & Co. KG offers the establishment of five shallow geothermal probes, each 90 meters deep, for 49.749,70€ at most. This corresponds to 110,55€ per meter drilled. When applying the rule of thumb which indicates that on average 21 meters need to be drilled per kW heating capacity, a geothermal probe of 700m depth delivers a heating capacity of around 33 kW, while a 450m deep geothermal probe only delivers a heating capacity of 21 kW. Indeed, the energy output of the medium-deep geothermal probe accounts for 156% of the shallow geothermal probe´s energy output, however, its costs account for 274% of the shallow probe´s costs. This comparison clearly demonstrates that the AM12/50´s service as outlined in the case study in Chapter 3.2 is not competitive.

However, this statement does not mean, that the entire undertaking of converting the AM12/50 and operating with it is obsolete, but that improvement measures must be taken. On the one hand, a product needs to be offered that has clear advantages for the customer compared to cheaper shallow geothermal probes. On the other hand, the costs of drilling need to be lowered to be able to offer a lower and more competitive sales price. In comparison to shallow probes, the medium-deep probe has the fundamental advantage that the necessary depth is established by only one borehole instead of several shallow ones. Since a distance of a few meters need to be maintained between geothermal wells, a multi-well solution needs adequate space. Enough space not always is available, like in urban areas, thus only a medium-deep probe comes into question. In case enough space is available, a product that can outperform shallow geothermal probes is required. Such a product would be a medium-deep geothermal probe that delivers temperatures of around 30°C. With this temperature, it is possible to operate low-temperature applications such as underfloor heating making an installation of a heat pump unnecessary. As a result, the customer not only saves costs for the installation of the heat pump but also saves the heat pump´s operating costs. In fact, this would justify higher drilling costs, nevertheless, it must be aimed to reduce them. In order to lower the drilling costs, several potential savings exist. These potential savings vary significantly among projects because they depend on the client, the location, the geology, and the conditions on site among other factors. Essentially, every medium-deep drilling project has a different cost structure. The challenge is to evaluate for which project an attractive offer can be made. By guess, some projects allow drilling cost reductions of up to 20.000€. As highlighted in the sensibility analysis, the casing costs, the personnel costs, and the logistical costs are relatively high and hold savings potential. This is because, depending on the formation, the casing string does not have to run to the total depth. Staff costs can be saved because the salaries calculated in the case study are based on German standards. In practice, when deploying the existing crews of CMB Well Services S.R.L., Romanian salary standards take effect, thus, personnel costs are considerably lower. In addition to the cost savings, the profit margin could be reduced too, for instance to 10%, so the sales price can further be lowered. With the help of these corrective actions, the sales price would amount to 103.389,56€, which would give a price per meter drilled of 147,70€. In my estimation, with this sales price and the option of not needing a heat pump, competitiveness is established. The following KPIs demonstrate that also with a sales price of 103.389,56€, the investment into the conversion of the AM12/50 can still be economically justified. In case the realistic number of 35 projects is annually carried out, an annual net profit of 250.015,15€ (Austria) respectively 261.528,40€ (Germany) accumulates. The corresponding ROIs are 16,31% respectively 17,07%, while the payback periods are two years and nine months respectively two years and eight months.[341]

Finally, I can give the following recommendation to CMB Well Services S.R.L. regarding the conversion of the workover rig. For converting the rig, the focus should be on finding the right balance between installing new and secondhand equipment. It should be aimed to settle the CAPEX at around 1.000.000€ or even less, without having to accept technical, capacitive, or other qualitative limitations. Additionally, it should be attempted to fit the rig with as much electrically driven equipment as possible. That way, rig operation produces less noise and CO_2 emissions, which can be a decisive parameter in obtaining potential projects.

When it comes to sales, in my opinion, besides making the sales price more attractive, the task with the greatest urgency is to identify a target group, to which the product is tailored and presented. In any case, I recommend approaching multipliers, like city administrations or commercial chains because cooperation with these could lead to several projects. However, I see the most potential in the public sector. Public buildings, which have an area of several hundred square meters and may be located in urban areas, are predestined to be equipped with medium-deep geothermal probes. Especially, in the introductory phase of the product, the public sector certainly is more receptive than other sectors. This is because the public sector has pressure to act as a role model in terms of sustainability and, therefore, is forced to act. Other potential target groups that

[341] Calculations in Appendix E

should be contacted in addition to the public sector are energy communities, housing cooperatives and commercial chains with their own existing buildings.

All in all, I support the conversion of the AM12/50. On one side, the financial risks are manageable, on the other side, there is the chance to be a pioneer in a promising market. Especially in the initial phase, it is probably not a sure-fire success, so strenuous work has to be done in terms of sales and distribution in order to achieve a capacity utilization of the rig that makes the venture economically feasible.

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Appendix A

Austrian and international standards regarding geothermal energy and geothermal drilling.

- ÖNORM B 2538: Wasserversorgung – Anforderungen an Wasserversorgungssysteme und deren Bauteile außerhalb von Gebäuden; ergänzende Bestimmungen zu ÖNORM EN 805 (Ausgabe: 2018-02-01)
- ÖNORM B 2601: Wassererschließung – Brunnen (Ausgabe: 2016-03-15)
- ÖNORM B 5014-2: Sensorische und chemische Anforderungen und Prüfung von Werkstoffen im Trinkwasserbereich - Teil 2: Zementgebundene Werkstoffe (Ausgabe: 2017-01-01)
- ÖNORM EN ISO 14688-1: Geotechnische Erkundung und Untersuchung - Benennung, Beschreibung und Klassifizierung von Boden - Teil 1: Benennung und Beschreibung (Ausgabe: 2020-12-01)
- SIA 384/6: Erdwärmesonden (gültig ab 2010-01-01)
- VDI-Richtlinie 4640 - Blatt 2: Thermische Nutzung des Untergrunds – Erdgekoppelte Wärmepumpenanlagen (Ausgabe: Juni 2019)
- ÖWAV-Regelblatt 207: Thermische Nutzung des Grundwassers und des Untergrunds – Heizen und Kühlen (2009) [342]

[342] Refer to Das Land Steiermark- Wasserwirtschaft, https://www.wasserwirtschaft.steiermark.at/cms/dokumente/10178489_4578743/4bd11ff3/Strategiepapier%20Erdw%C3%A4rme%202.0.pdf (accessed: 31.03.2023)

Appendices B

Complete list of investigated German water well builders that offer the drilling of geothermal wells.

State	Name of company
Bavaria	Stockbauer Bohr und Brunnenbau GmbH[343]
Bavaria	Bohr- und Brunnenbau Dippold e. K.[344]
Baden-Württemberg	Edward Michalik GbmH[345]
Baden-Württemberg	Goller Bohrtechnik GmbH & Co. KG[346]
Rhineland-Palatinate	Handke Brunnenbau GmbH[347]
Rhineland-Palatinate	Ehlen & Söhne GmbH[348]
Saarland	Hölker Bohrunternehmen GmbH[349]
Hesse	H. Pettenpohl Tiefbohrges. mbH[350]

[343] Refer to Stockbauer Bohr und Brunnenbau GmbH, https://www.brunnenbau-stockbauer.de/erdwaermebohrungen.htm (accessed: 09.05.2023)
[344] Refer to Bohr- und Brunnenbau Dippold e. K., https://brunnenbau-dippold.de/leistungen/#waermepumpe (accessed: 09.05.2023)
[345] Refer to Edward Michalik GmbH, https://www.michalik-brunnenbau.de/ (accessed: 09.05.2023)
[346] Refer to Goller Bohrtechnik GmbH & Co. KG, https://brunnenbaugoller.de/ (accessed: 09.05.2023)
[347] Refer to Handke Brunnenbau GmbH, https://www.handke-brunnenbau.de/referenzen/ (accessed: 09.05.2023)
[348] Refer to Ehlen & Söhne GmbH, https://ehlen-erdbohrungen.com/erdwaerme (accessed: 09.05.2023)
[349] Refer to Hölker Bohrunternehmen GmbH, https://www.hoelker-bohrunternehmen.de/ (accessed: 09.05.2023)
[350] Refer to H. Pettenpohl Tiefbohrges. mbH, https://www.brunnensanierung.de/brunnenbau/ (accessed: 09.05.2023)

Hesse	Kaestner-Brunnenbau-GmbH[351]
North Rhine-Westphalia	Webru Brunnenbau GbR[352]
North Rhine-Westphalia	Lütkehaus Brunnenbau GmbH[353]
Lower Saxony	Sven Hansen Wasser- und Brunnenbautechnik[354]
Lower Saxony	Hartmann Brunnenbau GmbH[355]
Lower Saxony	Erdbohrtechnik Brüntjen GmbH[356]
Hamburg	Nord Bohr und Brunnenbau GmbH[357]
Schleswig-Holstein	Henningsen Erdwärmesonden & Brunnenbau e.K.[358]
Schleswig-Holstein	Ivers Brunnenbau GmbH[359]
Mecklenburg-Vorpommern	Brunnenbau Hinrichs[360]

351 Refer to Kaestner-Brunnenbau-GmbH, https://www.brunnenbau-kaestner.de/geothermiebohrung/ (accessed: 09.05.2023)
352 Refer to Webru Brunnenbau GbR, http://www.webru-brunnenbau.de/html/fuhrpark.html (accessed: 09.05.2023)
353 Refer to Lütkehaus Brunnebau GmbH, https://luebru.de/leistungen/erdwaermebohrungen/ (accessed: 09.05.2023)
354 Refer to Sven Hansen Wasser- und Brunnenbautechnik, https://www.hansen-brunnenbau.de/erdwaerme/ (accessed : 09.05.2023)
355 Refer to Hartmann Brunnenbau GmbH, https://www.wasserwasserwasser.de/index.php/referenzen-2 (accessed: 09.05.2023)
356 Refer to Erdbohrtechnik Brüntjen GmbH, https://erdbohren.de/erdwaerme/ (accessed: 09.05.2023)
357 Refer to Nord Bohr und Brunnenbohr GmbH, https://nord-bb.de/de/leistungen/brunnenbau/brunnenbohrungen%e2%80%8b/ (accessed: 09.05.2023)
358 Refer to Henningsen Erdwärmesonden & Brunnenbau e.K., https://www.brunnenbau-henningsen.de/erdwaermebohrungen/ (accessed: 09.05.2023)
359 Refer to Ivers Brunnenbau GmbH, https://www.ivers-brunnenbau.de/erdwaerme/ (accessed: 09.05.2023)
360 Refer to Brunnenbau Hinrichs, https://bbh-mv.de/erdwaermesonden/ (accessed: 09.05.2023)

Brandenburg	Gesche Brunnenbaugesellschaft Lebus GmbH[361]
Brandenburg	aQua-thermic Bohrgesellschaft mbH[362]
Berlin	Ingenieurbüro Beneke Baugrund und Geotechnik[363]
Saxony-Anhalt	Schubert-Brunnenbau GmbH[364]
Saxony	Brunnenbau Thomas[365]
Saxony	Dipl. Ing. W. Engelmann[366]
Thuringia	Brunnenbau Conrad GmbH[367]

361 Refer to Gesche Brunnenbaugesellschaft Lebus GmbH, https://www.brunnenbau-lebus.de/geothermie (accessed: 09.05.2023)
362 Refer to aQua-thermic Bohrgesellschaft mbH, https://www.aqua-thermic.com/erdwaerme.html (accessed: 09.05.2023)
363 Refer to Ingenieurbüro Beneke Baugrund und Geotechnik, https://www.beneke-geotechnik.de/erdwaermebohrungen.html (accessed: 09.05.2023)
364 Refert to Schubert-Brunnenbau GmbH, ttps://www.schubert-brunnenbau.de/erdwaermesonden.html (accessed: 09.05.2023)
365 Refer to Brunnenbau Thomas, https://www.brunnenbau-thomas.de/erdwaerme/ (accessed: 09.05.2023)
366 Refer to Dipl. Ing. W. Engelmann, https://brunnenbau-engelmann.de/erdw.html (accessed: 09.05.2023)
367 Refer to Brunnenbau Conrad GmbH, http://www.brunnenbau-conrad.de/Produkte.htm (accessed: 09.05.2023)

Appendix C

Notes of the interview with Mr. Eibl Jürgen (Senior Drilling Engineer at OMV Petrom), 19.05.2023

Ausrüstung und Fähigkeiten der Bohranlage richten sich nach Projekt/Kundenwünschen, also Aufrüstung der Anlage abhängig von Well Objectives;

Well Objectives (Rahmenbedingungen) definieren: 9 5/8 inches Casings setzen (gängige Größe und somit nicht sehr teuer), mit geringer Wandstärke, kann über gesamte Teufe bis 700m gesetzt werden, Größe des Bohrmeißels für diesen Fall ist 12 1/4 inches ;

Bei der Umrüstung von alten Erdölbohrungen zu Geothermiebohrungen werden auch 9 5/8 Casings installiert;

Man braucht Conductor (13 3/8 inches), sollte im Optimalfall die Baufirma, welche den Bohrplatz herrichtet, installieren; Kleinere Workover Anlagen können diese Rohrgröße nicht verbauen, da der Drehtisch/Arbeitsbühne (limitierender Faktor) nicht groß genug ist, 20-30 Meter ist der Conductor abgeteuft, Conductor agiert als Fundament einer Bohrung, hat Funktion gegen Auswaschen des obersten Bohrabschnitts;

Vertikale Bohrung, nicht abgelenkt;

Beim Einbauen des Casings erreicht man die maximale Hakenlast, gängigstes Casing Gewicht ist 36 pounds per feet;

Gewicht der Casings wird in Luft gerechnet und nicht in Wasser/Spülung, damit Sicherheitsfaktor beinhaltet ist.

Man braucht hier nur ein Surface Casing, da Bohrung mitteltief ist, BOP kommt aufs Surface Casing drauf und nicht auf Conductor;

Wenn BOP auf Conductor- Bohrungen kann zwar geschlossen werden, allerdings geht der Druck seitlich zwischen Conductor und Gestein durch- Blow Out. Seichtgas ist hier also ein großes Problem; Lässt man kontrolliert entweichen oder wird totgepumpt, sind meistens geringe Volumina;

Lösung ist ein Diverter- funktioniert wie annular BOP, schließt um Gestänge ab und leitet Kick kontrolliert ab; Diverter ist von Anfang an auf Bohrung drauf, um Problemen mit Seichtgas vorzubeugen, Diverter muss unter Arbeitsbühne passen, normalerweise sind Diverter maximal 1m hoch;

Workover BOP als Alternative zum Diverter, dann muss allerdings die Bohrgarnitur durchpassen, Diverter gibt es in sämtlich Rohrgrößen; Innendurchmesser von Diverter muss groß genug sein, damit 12 1/4 inches Bohrgestänge durchpasst;

Naheliegendste Lösung für Rotary System- kleine Variante eines Topdrives oder Rotary Head; 700m Teufe sind mit Topdrive von geringer Leistung machbar. Drehmoment reicht aus. Topdrive braucht eigene Energieversorgung;

Zirkulieren der Bohrung: Mud pump, Tanks, Shale Shakers sind notwendig, Volumen der Tanks sollte das doppelte des Bohrlochvolumens sein (ohne Bohrgestänge);

Mud pumps können ganzes Zirkulationssytem in Bewegung bringen, Hilfspumpen sind nicht von Nöten;

Amerikanische Zirkulation- Pit mit Erhebung in der Mitte, Flüssigkeit fließt darüber, Festkörper bleiben hängen;

Bei einem solchen Projekt, sollte alles aus einer Hand kommen, also komplette Projektabwicklung und keine zusätzlichen externe Gewerke wie Spülmeister oder Directional Driller;

Casings bringt der Casinglieferant;

Bohrplatz sollte so klein wie möglich gehalten werden, also nur Mannschaftscontainer, Auflage für Gestänge, Tanks, etc.

Mannschaft besteht aus Driller, 2 Floormen, 2-3 Roughnecks, Spülungsmitarbeiter, Reserve; Vermutlich braucht es 8 Crewmitglieder, Rig Mechaniker und Rig Elektriker bleiben in der Zentrale und kommen nur auf Bedarf;

Dauer des Projektes- zu Beginn wohl ca. eine Woche, wenn Team eingespielt ist, dann nur mehr ca. 4 Tage, normalerweise ROP von 20-30m pro Stunde

Lärmemission der Anlage ist entscheidend, ob in Nacht gebohrt werden kann;

Bohren an sich dauert nicht so lange aber Zusammensetzung des Bohrgestänges kann in diesem Fall 6-8 Stunden dauern;

Notes of the interview with Mr. Heemann Bernd (General Manager Austria & Business Development Manager Geothermal at MB Well Services GmbH), 04.05.2023

Hakenlasten- welches Gewicht an Dasings muss abgesenkt werden, davon die mögliche Teufe ableiten;

Verschieden Teufen: flache Geothermie, mitteltiefe Geothermie und tiefe Geothermie;

Mitteltiefe Geothermie (1000m bis 1500m)- hier braucht es Hakenlasten von 150t bis 250t;

Tiefe Geothermie- Hakenlasten von über 350t;

Markt für mitteltiefe Geothermie vorhanden- MB Well Services GmbH konzipiert Anlage für mitteltiefe Geothermie, soll vor allem für den städtischen Bereich geeignet sein (geräuscharm, wenig Emissionen, kleiner Fußabdruck, schlank), 250t Hakenlast für 1200m bis 2500m;

Bohrlochsicherheit ist in der BVOT geregelt;

Projektabwicklung- Behördenabwicklung soll demnächst zügiger gehen, Untergrunduntersuchung, Machbarkeitsstudie etc. kann mehrere Monate (6-12 Monate) dauern bis Genehmigung erteil wird, Planung hängt von Location ab (Stadt, Natur, etc.), Behördenverfahren sollen beschleunigt werden;

Kosten der Bohrung- nur der Tagessatz der Anlage (inklusive Team) kann bis zu 25.000€ sein, keine Planung etc. inkludiert;

Durchmesser der Bohrung und Abfolge der Casings hängt von gewünschtem Durchmesser am tiefsten Punkt ab;

Notes of the interview with Mr. Misch David (Montanuniversität Leoben, Lehrstuhl füf Erdölgeologie), 22.05.2023

Potenzial in der mitteltiefen Geothermie nicht wirklich erfasst, liegt hauptsächlich an zu geringen Temperaturen (30° Celsius oder etwas mehr);

Potenziale in der mitteltiefen Geothermie reichen aus für Space Heating und für individuelle Gebäude (öffentliche Gebäude);

Reservoir Charakterisierungen finden in diesen Tiefen (400-600m) nicht statt, da zu aufwendig in Relation mit Energieoutput, deshalb keine flächendeckende Kartierung des Untergrunds in diesen Bereichen;

Notwendige Fließrate von 100 Liter pro Sekunde notwendig für tiefe Geothermie, erreicht man in seichten Lagen kaum;

Geothermieprojekte brauchen die 10-fache Permeabilität von Erdölprojekte;

Es gibt einzelne wenige Gegenden in Österreich (Wiener und Grazer Becken), die zulassen würden, dass aus flachen Reservoirs produziert wird, weil die Permeabilitäten ausreichen. Allerdings nur für Niedrigtemperaturanwendungen möglich, nicht für Fernwärme;

Ates (Aquifer thermal energy storage) könnte eine mögliche seichte Anwendung sein- Abwärme wird in den Untergrund verpresst und bei Bedarf wieder produziert; Wasser wird eingebracht, deshalb braucht man ein permeables Gestein; Wasser wird aufgewärmt eingebracht, somit erhitzt sich das Gestein rundherum; In Holland werden einige Ates Projekte durchgeführt;

Bei Anwendung von Sonde ist die Fündigkeit kein Risiko, bei Dublette schon, dies stellt eine große Chance dar. Finanzierung mit geringerem Risiko, deshalb eher Sonde als Dublette im mitteltiefen Bereich;

Sonde könnte flächendeckend verwendet werden, Dublette nicht;

Molasse Becken- hier existieren Seichtgasreservoire, deshalb Bohrlochsicherheit ein großes Thema;

Seichtgas kann grundsätzlich nirgendwo ausgeschlossen werden, in manchen Regionen weiß man aber um die Existenz, weil Vorkommen gut erfasst;

Bohrlochsicherheit an lokale Gegebenheiten anpassen, man muss es nicht immer anbieten;

Immer wieder Vorfälle mit Brunnenbauern und Seichtgasreservoire, dann brauchen diese Hilfe von OMV etc., also von Experten;

Überdruckbereiche im Gestein können in diesen Tiefen fast gänzlich ausgeschlossen werden, kommt nur bei tiefen Bohrungen vor;

Gradient- 12° C Oberflächentemperatur plus 29° C pro Kilometer im Wiener Becken, in Österreich findet man maximal 40° Celsius in Tiefen von 600 Meter vor;

Grundsätzliche Einschätzung: Markt für seichte und mitteltiefe Geothermie ist da und wird wachsen. Größtes Problem sind die hohen Investitionskosten und das Fündigkeitsrisiko;

Notes of the interview with Mr. Schellenberg Detlef (Controller at MB Well Services GmbH), 31.05.2023

Bei Erdölprojekt liegt das Risiko beim Kunden, die Bohrfirma wird nach Aufwand bezahlt;

Geothermieprojekte werden oftmals pauschal verrechnet, somit liegt das Risiko einer Verzögerung des Projektes bei der Bohrfirma;

Es gibt vier Kostenblöcke: Personal, Maschinerie, fremdvergebene Leistungen (Logistik, Kräne etc.), Gemeinkosten (Controlling, Projektmanagement, Geschäftsführung etc.);

Faktoren beim Personal- woher kommt die Crew (Rumänien, Österreich, Deutschland, etc.), Schichtsystem, Zusammenstellung der Mannschaft (Toolpusher, Driller, Roughneck etc.)

Faktoren bei der Maschinerie- Anschaffungskosten der Anlage, Umrüstungskosten, Kosten des zusätzlichen Equipments, technische Lebensdauer des Equipments (nicht buchhalterisch), Abschreibung pro Jahr, Betriebsstunden pro Jahr, Wartungskosten und Reparaturkosten;

Gemeinkosten werden mit einem Prozentsatz berechnet;

Notes of the interview with Mr. Spörker Thomas (Bundesministerium für Finanzen, Abteilung Bergbau), 12.05.2023

Mineralrohstoffgesetz- Bohrungen tiefer als 300m benötigen die Bewilligung der Montanbehörde, in der Bewilligung muss auch Verrohrungsschema festgelegt werden;

Bohrlochbergbauverordnung- Paragraph 32 sind Vorgaben zur Verrohrung und Zementierung festgelegt;

Aufbrechen des Gesteines im unverrohrten Bereich muss durch Verrohrung verhindert werden;

Zementation muss so erfolgen, sodass keine Kommunikation zwischen zwei unterschiedlichen Horizonten entsteht und keine Kommunikation zur Oberfläche besteht;

Unternehmen ist für Verrohrungsschema verantwortlich; Dieses wird eingereicht und von der Montanbehörde bewilligt oder eben abgelehnt;

Technische Normen sind zum Beispiel die API Standards oder die BVEG, diese geben technische Richtlinien für Verrohrung, Zementation und Absperreinrichtung vor, wenn man sich als Unternehmen an diese Vorgaben hält, stimmt die Behörde so gut wie immer zu;

Notes of the interview with Mr. Wirth Stefan (HSEQ Director of Christof Industries Global GmbH) 23.06.2023

Rig power reicht wohl nicht aus für Rotary Head , Anschluss an das Stromnetz oder Aggregat mit 50 kW ist notwendig; Benötigter Rotary Head ist eher klein und verringern die clear height nur um 2-3m (inkl. Hook and Block);

Drill string besteht aus 650m Bohrgestänge und 50m Schwerstangen; Bohrgestänge mit 5 inches Durchmesser ausreichend;

Für Bohrlochsicherheit kann auch ein kleiner BOP mit 1500psi Arbeitsdruck verwendet werden; Dieser wird mit einem Flange und einer Spool am Conductor befestigt; Aus Gründen der Vereinfachung geht man hier von einem BOP aus, welcher manuell betätigt werden kann; Somit ist keine Schließanlage von Nöten; Durch ein Ventil in der Spool kann Druck entweichen und in sicherer Distanz abgelassen werden; Sehr individuelle Anfertigung, bei der man nur eine Mutmaßung bezgl. Preis machen kann, Schätzung liegt bei ca. 40.000€;

Bezüglich der Auslastung der dieselbetriebenen Maschinen wird ein Auslastungsfaktor von 60% angenommen;

Notes of the interview with Mr. Uhlig Stefan (CEO of GeoTec Consult Ingenieurbüro Uhlig + Partner, Markt Schwaben, Germany), 08.05.2023

Individuelle Betrachtung der Projekte im mitteltiefen Bereich, da es schwer zu sagen ist, ob es flächendeckend einen Markt für mitteltiefe Geothermie gibt; Hängt davon ab, ob Sonde oder Brunnen; Sonde eventuell flächendeckend einsetzbar, Hydrogeothermie nur in speziellen Bereichen;

Mitteltiefe und tiefe Bohrungen durch Brunnenbauer (Brunnenbohrgeräte) von 1800m Tiefe wurden bereits mit 40t Anlage und Seilkernbohrung von 1460m Tiefe mit 30t Anlage abgeteuft; Beispielunternehmen sind Abt Wasser- und Umwelttechnik GmbH und Ochs Bohrgesellschaft mbH;

Beispiele von Tiefbohrfirmen die ursprünglich aus dem Brunnenbau kommen und Anlagen für den mitteltiefen Bereich haben sind Anger´s Söhne und Daldrup & Söhne AG;

Brunnenbauer haben auch Geräte mit 50-60t Hakenlasten;

Hakenlasten vor allem um Casings zu heben; Flache Bohrungen haben keine Casings und es wird bei diesen Bohrungen auch kaum Bohrlochsicherheit (BOP, etc.…) verwendet;

Ab 600m Tiefe können schon Kohlenwasserstoffe vorkommen, daher ist Bohrlochsicherheit wichtig;

Mitteltiefe Geothermie ist kompliziert- ist Bohrlochsicherheit von Nöten oder kann darauf verzichtet werden? Bei tiefer Geothermie braucht man sowieso einen BOP etc., bei flacher Geothermie wird kaum Bohrlochsicherheit verwendet;

Mehr Energie durch geothermischen Brunnen als durch Sonde;

Bei über 200kW Energieentnahme aus dem Erdreich braucht es eine bergrechtliche Bewilligung in Deutschland (weil Bodenschatz), darunter nicht;

Bei unter 200kW und unter 100m Bohrtiefe muss man sich selber mit Wasserrechtsbehörden usw. beschäftigen, ansonsten kümmert sich das Bergamt um alles (Bergamt unterstützt- sind an der Gewinnung von Bodenschätzen interessiert);

Alternative Möglichkeit zur Bohrung- alte Erdölbohrungen für geothermische Zwecke verwenden oder Bohrungen in ehemalige Kohlebergwerksschächte abteufen;

Entscheidender Parameter- Wärmeleitfähigkeit des Gebirges- also heat flux density;

Wirtschaftlichkeit eines mitteltiefen Projektes unterscheidet sich stark zwischen verschiedenen Projekten;

Wasserwirtschaftsämter- lassen in manchen Gebieten nur Bohrungen von gewisser Tiefe zu, da es Bedenken gibt, dass durch schlechte Bohrarbeit eine hydraulische Verbindung zwischen zwei Grundwasserstauer hergestellt wird;

Zementierung von Sonden oft nicht in gewünschter Qualität möglich, sodass eine hydraulische Verbindung zwischen zwei Grundwasserstauern hergestellt wird- Einsatz von Casings könnte diese Problematik lösen;

Einsatz von Casings und sonstigen Bohrlochsicherheiten- ist das wirtschaftlich? Gradwanderung, da sehr teures Projekt- zahlen die Kunden das?

Kundschaft eher nicht im privaten Bereich;

Appendix D

Data on which the sensitivity analysis of the OPEX in Chapter 3.4 is based on is presented in the following table. The data table regarding the sensitivity analysis of the CAPEX has the exact same structure and the, therefore, required values (purchase costs of equipment) were taken from Table 4. Due to the immense size, the data table cannot be displayed here in any reasonable format.

Pers. costs [%]	**Pers. costs [€]**	**Equ. costs [%]**	**Equ. costs [€]**	**Mat. costs [%]**	**Mat. costs [€]**	**Misc. costs [%]**	**Misc. costs [€]**	**Total project-related costs [€]**
130%	32 206,81	100%	13 957,86	100%	32 801,20	100%	24 881,52	103 847,39
120%	29 729,36	100%	13 957,86	100%	32 801,20	100%	24 881,52	101 369,94
110%	27 251,92	100%	13 957,86	100%	32 801,20	100%	24 881,52	98 892,49
100%	24 774,47	100%	13 957,86	100%	32 801,20	100%	24 881,52	96 415,05
90%	22 297,02	100%	13 957,86	100%	32 801,20	100%	24 881,52	93 937,60
80%	19 819,58	100%	13 957,86	100%	32 801,20	100%	24 881,52	91 460,15
70%	17 342,13	100%	13 957,86	100%	32 801,20	100%	24 881,52	88 982,71
100%	24 774,47	130%	18 145,22	100%	32 801,20	100%	24 881,52	100 602,40
100%	24 774,47	120%	16 749,43	100%	32 801,20	100%	24 881,52	99 206,62
100%	24 774,47	110%	15 353,64	100%	32 801,20	100%	24 881,52	97 810,83
100%	24 774,47	100%	13 957,86	100%	32 801,20	100%	24 881,52	96 415,05
100%	24 774,47	90%	12 562,07	100%	32 801,20	100%	24 881,52	95 019,26
100%	24 774,47	80%	11 166,29	100%	32 801,20	100%	24 881,52	93 623,48
100%	24 774,47	70%	9 770,50	100%	32 801,20	100%	24 881,52	92 227,69
100%	24 774,47	100%	13 957,86	130%	42 641,56	100%	24 881,52	106 255,41
100%	24 774,47	100%	13 957,86	120%	39 361,44	100%	24 881,52	102 975,29
100%	24 774,47	100%	13 957,86	110%	36 081,32	100%	24 881,52	99 695,17
100%	24 774,47	100%	13 957,86	100%	32 801,20	100%	24 881,52	96 415,05
100%	24 774,47	100%	13 957,86	90%	29 521,08	100%	24 881,52	93 134,93
100%	24 774,47	100%	13 957,86	80%	26 240,96	100%	24 881,52	89 854,81
100%	24 774,47	100%	13 957,86	70%	22 960,84	100%	24 881,52	86 574,69
100%	24 774,47	100%	13 957,86	100%	32 801,20	130%	32 345,98	103 879,50
100%	24 774,47	100%	13 957,86	100%	32 801,20	120%	29 857,82	101 391,35
100%	24 774,47	100%	13 957,86	100%	32 801,20	110%	27 369,67	98 903,20
100%	24 774,47	100%	13 957,86	100%	32 801,20	100%	24 881,52	96 415,05
100%	24 774,47	100%	13 957,86	100%	32 801,20	90%	22 393,37	93 926,89
100%	24 774,47	100%	13 957,86	100%	32 801,20	80%	19 905,22	91 438,74
100%	24 774,47	100%	13 957,86	100%	32 801,20	70%	17 417,06	88 950,59

Appendix E

Calculations, the figures presented in the Conclusion are based on.

KPIs when annually realizing 35 projects with a sales price of 136.379,08€:

$$Net\ profit = EBIT * (100\% - Corporate\ income\ tax)$$

$$Project\ net\ profit\ (Austria) = 17.788{,}57€ * (100\% - 24\%) = 13.519{,}31€$$

$$Annual\ net\ profit\ (Austria) = 35 * 13.519{,}31€ = 473.175{,}85€$$

$$Project\ net\ profit\ (Germany) = 17.788{,}57€ * (100\% - 20{,}5\%) = 14.141{,}91€$$

$$Annual\ net\ profit\ (Germany) = 35 * 14.141{,}91€ = 494.966{,}85€$$

$$ROI = \frac{Annual\ net\ profit}{Costs\ of\ investment\ (CAPEX)} * 100$$

$$ROI\ (Austria) = \frac{473.175{,}85€}{1.532.489€} * 100 = 30{,}88\%$$

$$ROI\ (Germany) = \frac{494.966{,}85€}{1.532.489€} * 100 = 32{,}30\%$$

$$Annual\ CF = Annual\ net\ profit + \ annual\ imputed\ costs$$

$$Annual\ CF\ (Austria) = 473.175{,}85€ + 35 * (6.491{,}87€ + 2.465{,}99€) = 786.700{,}95€$$

$$Annual\ CF\ (Germany) = 494.966{,}85€ + 35 * (6.491{,}87€ + 2.465{,}99€) = 808.491{,}95€$$

$$Payback\ period = \frac{Costs\ of\ Investment}{Annual\ cash\ flow}$$

$$Payback\ period\ (Austria) = \frac{1.532.489€}{786.700{,}95€} = 1{,}95\ years\ [\sim 1\ year\ and\ 11\ months]$$

$$Payback\ period\ (Germany) = \frac{1.532.489€}{808.491{,}95€} = 1{,}90\ years\ \ [\sim 1\ year\ and\ 11\ months]$$

KPIs when annually realizing 35 projects with a sales price of 103.389,56€:

$$EBIT = Revenue - Project\ costs - Overhead\ costs$$

$$Project\ EBIT = 103.389{,}56€ - 76.415{,}05€ - 17.575{,}46€ = 9399{,}05€$$

$$Annual\ EBIT = 35 * (103.389{,}56€ - 76.415{,}05€ - 17.575{,}46€) = 328.966{,}75€$$

$$Net\ profit = EBIT * (100\% - Corporate\ income\ tax)$$

$$Project\ net\ profit\ (Austria) = 9399{,}05€ * (100\% - 24\%) = 7.143{,}29€$$

$$Annual\ net\ profit\ (Austria) = 35 * 9399{,}05€ = 250.015{,}15€$$

$$Project\ net\ profit\ (Germany) = 9399{,}05€ * (100\% - 20{,}5\%) = 7.472{,}24€$$

$$Annual\ net\ profit\ (Germany) = 35 * 7.472{,}24€ = 261.528{,}40€$$

$$ROI = \frac{Annual\ net\ profit}{Costs\ of\ investment\ (CAPEX)} * 100$$

$$ROI\ (Austria) = \frac{250.015{,}15€}{1.532.489€} * 100 = 16{,}31\%$$

$$ROI\ (Germany) = \frac{261.528{,}40€}{1.532.489€} * 100 = 17{,}07\%$$

$$Annual\ CF = Annual\ net\ profit + \ annual\ imputed\ costs$$

$$Annual\ CF\ (Austria) = 250.015{,}15€ + 35 * (6.491{,}87€ + 2.465{,}99€) = 563.540{,}25€$$

$$Annual\ CF\ (Germany) = 261.528{,}40€ + 35 * (6.491{,}87€ + 2.465{,}99€) = 575.053{,}50€$$

$$Payback\ period = \frac{Costs\ of\ Investment}{Annual\ cash\ flow}$$

$$Payback\ period\ (Austria) = \frac{1.532.489€}{563.540,25€} = 2{,}72\ years\ [\sim 2\ years\ and\ 9\ months]$$

$$Payback\ period\ (Germany) = \frac{1.532.489€}{575.053,50€} = 2{,}66\ years\ \ [\sim 2\ years\ and\ 8\ months]$$