FROM COAL MINING TO HEAT MINING
Perspectives of value creation for the most venerable European industry

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Introduction

In January 2019 the German Coal Commission and the Federal Government came up with a game changing decision for the national energy market. Until 2035 – 2038 at latest – the country will get out of the combustion of coal and therefore has to replace 45 GW electrical power and even more heat by renewable sources. The reduction will happen stepwise: 12,5 GW by 2022 (same year when the last nuclear power plant will be shut down), 17 GW by 2030, and 45 GW by 2035/37. Geothermal energy shall become a major player in the new energy mix, especially for the heat market. This transition will become by far the largest industrial and social changing process in Germany´s history. Several pilot projects are introduced in order to enable the industry and the existing energy-infrastructure for this transition process. The new national Fraunhofer-Institute for Energy Infrastructures and Geothermal Energy shall orchestrate the development, together with the implementation of so-called Real-Laboratories for deep geothermal energy in the hardcoal mining area of the Ruhr Valley and in the lignite production region between Cologne and Aachen. The TRUDI Metropolitan Underground Laboratories for the exploration and large-scale development of hydrothermal potentials in the Ruhr area is located in the south of Bochum. TRUDI is at the same time the flagship experiment for underground storage of heat and cold in former coal mines, and for the supply of thermal energy from geothermal water from various sources into the district heating systems of the Rhine-Ruhr region - using the district heating network Bochum-South (115 MWth) as an example.

Energy infrastructure and its geological setting in Western Germany

The Rhine-Ruhr Metropolitan Region (RRR), with a population of around ten million, is one of the three largest urban areas in Europe, alongside Paris and London; more than 5 million people live in the Ruhr Valley alone. Based on the industrial developments in the coal and steel and energy sectors, a globally unique integrated heating system has been created in the Rhine-Ruhr region in recent decades. The Ruhr district heating network alone supplies 6,500 GWh/a with an installed capacity of 2,310 MWth; the main heat generators are fossil-fired plants (coal, natural gas), waste incineration and industrial plants (including steel production). The network has a length of over 2,000 km, consisting of primary (180°C) and 25 secondary networks (70-130°C); CO_2 emissions from heat generation amounted to approx. 300 million t/a in 2012 (BET 2013). The connection of the Ruhr network with the district heating pipeline Niederrhein (620 km, 844 MWth, 981 GWh/a) between Duisburg and Bottrop will lead to the largest combined heat and power network in Europe in 2019.

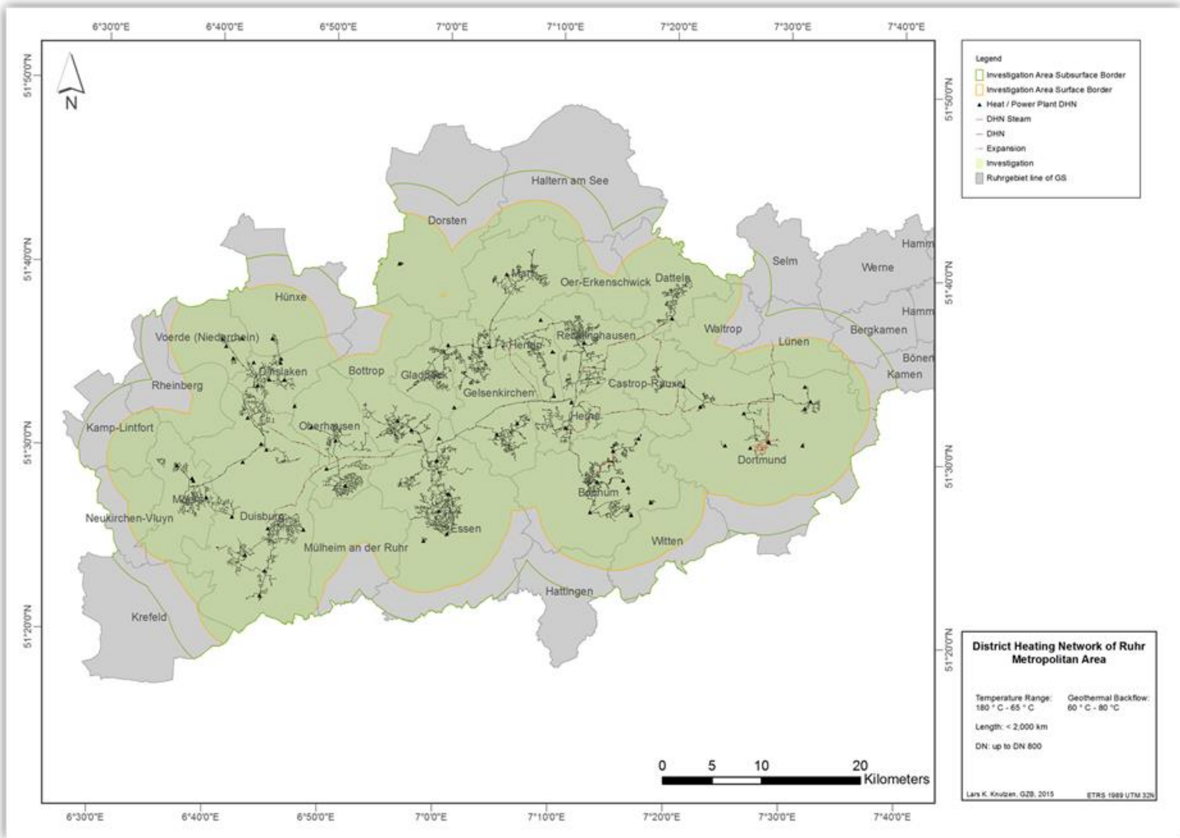

Figure 1: *Ruhr metropolitan district heating network with fossil heat generation plants.*

Efforts to convert the district heating systems on the Rhine and Ruhr are aimed at this end:
- Replacing older fossil-fuel power plants with new, efficient renewable energy plants
- Gradual reduction of the network temperature, Power to Heat supplement if necessary
- Seasonal heat storage facilities (e.g. underground mining infrastructure)

Current research projects on the potentials of deep geothermal energy in the Rhine-Ruhr region concentrate on two fields: a) conventional hydrothermal reservoirs in fissured sedimentary reservoir rocks below the coal-bearing geological formations and b) medium-deep reservoirs for mine water use and as seasonal heat reservoirs in the cavity structures of the crushed hard coal mountains (Bracke et al., 2016).

Potential hydrothermal reservoirs in western Germany are fractured sandstones and karstified limestones and dolomites. The carbonate rocks of the Devonian (especially mass limestones of the Middle Devonian) were deposited in NW-Europe in lagoon areas of the Rheno-hercynian shelf between reef bodies and mainland. They are found near the surface in the Northern Eifel near Aachen, in the Rhenish slate mountains and in the Sauerland. In the Wuppertal-Wulfrath area they are open with thicknesses of approx. 300m. From there they follow the general stratification in the direction of the North German basin. In the deeper underground of the Lower Rhine Bight as well as in the Ruhr area, limited statements on the distribution between 3000-7000m via deep boreholes in the Lower Rhine and the Munsterland 1 borehole are possible. Carbonates of the Lower Carboniferous are deposited above the Devonian mass limestones. They are divided into two large sedimentation areas. These include the coal limestone facies (Kohlenkalk) south/west of Essen to the northern Eifel, Belgium and the Netherlands with deposits of a carbonate platform on the shelf edge of the London-Brabant massif (reef limestone). For the Kulmfacies in the eastern Ruhr area and Westphalia with calcareous deep sea deposits (Calciturbidites / Plate Limestones) thicknesses of 200 m are assumed. Outcrops on the Lower Rhine already show karstification up to 1,000 m thickness.

In addition to the carbonates, potential hydrothermal reservoir rocks in NRW are Ruhr sandstone (e.g. Kaisberg, Graywacke) formations of the carbon as well as sandstone aquifers from the Triassic and Jurassic periods in the Bad Oeynhausen area, on the northern Lower Rhine as well as in the western and northern Munsterland. Due to the rather low porosities, hydrothermal circulation in the area of tectonic faults or in extensional tectonic fold / fracture structures may be considered.

The theoretical total geothermal potential of these formations in the Ruhr area sums up to approx. 92,300 GWh/a (thereof Devonian Mass Limestone: 59200; Kulm / Kohlenkalk (Lower Carboniferous): 10400; Grauwacken Namur B / Upper Carboniferous: 22700 GWh/a). This means that the potential exceeds the required amount of heat in the district heating network Ruhr by a factor of 10-15, depending on the expansion scenario. A very rough estimate would theoretically require 150 to 200 geothermal heating plants to provide that heat. In order to secure this very abstract approach, an investigation programme was launched for the creation of a valid data situation.

As an example for the Rhine-Ruhr region, the existing Bochum-Süd heating network (115 MWth) is to be converted to deep geothermal energy with the umbrella project TRUDI. The objective of TRUDI is a) the derivation of the necessary geoscientific and energy-technical decision bases for the energy industry in total NRW in the conversion of municipal heating systems from fossil to renewable energy sources and b) the creation of a development platform for technology providers in the conversion of their products from steam (nuclear and coal-fired power plants) to thermal water processes. The geological objectives of TRUDI are deep hydrothermal reservoirs at 4000-5000 m in folded sedimentary reservoir rocks of the Variscian basement and medium-deep reservoirs for seasonal heat storage in the basement and in the cavity structures of the crushed hard coal mining.

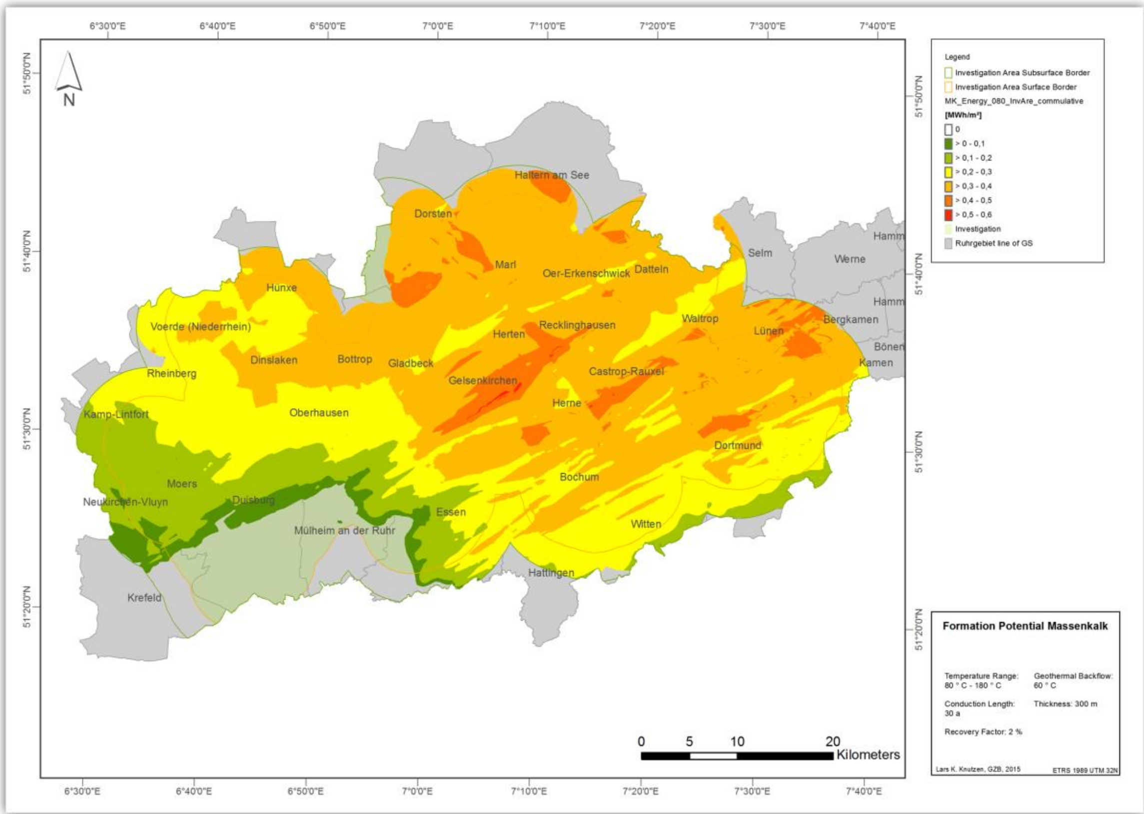

Figure 2: *Geothermal potential of Devonian limestone referred as Massenkalk with more than 300 m thickness, in 3,000 to 7,000 m depth, in temperature range of 80°-180°C (after Bracke et al., 2016)*

Use of mine water for district heating and seasonal heat storage in hard coal mines

The western part of Germany is still characterised by intensive mining activities that date back to Roman times and beyond. In addition to the extraction of hard coal and lignite, salt, iron ore, copper, zinc, lead and various minerals and building materials were and are still mined. Several thousand mines have been documented in the country, the majority of which have since been closed down, in particular due to changed economic conditions and the exhaustion of deposits. At the peak of German hard coal mining in the mid-1950s, more than 200 mines were in operation between Alsdorf in the Aachen area, Kamp-Lintfort on the Lower Rhine and Hamm in Westphalia. With the closure of the last Prosper Haniel colliery at the end of 2018, the hard coal industry in Germany became history. Subsequently, the area-wide sump measures are reduced by approx. 100 million m^3/a for the mine water and a controlled rise to approx. 300-500 m below ground level is initiated; from this level, pumping must continue permanently ("eternal loads").

However, the underground mine structures represent an enormous potential for grid-connected heat supply. In addition to the direct energetic use of mine water, seasonal storage can also close the gap between seasonal excess heat from power plant operation or industrial processes in summer and the corresponding amount of heat required in winter. The use of mine water from 600-1000 m depth for heat generation and seasonal storage is possible with different technical systems. A distinction has to be made between open and closed systems. The thermal water originates either from water retention in deep mines or from swamping measures in open-cast mines, whereby the mine water is actively pumped via pump systems and then discharged into an above-ground receiving watercourse.

In open well systems, the mine water is extracted from the mine workings exclusively for energetic purposes and returned to the mine workings elsewhere. In this case, open shafts or directional boreholes, which open up underground water-filled sections, are used and equipped with appropriate deep pump systems. With closed systems, the mine water and the existing mine infrastructure can be accessed indirectly. These are heat exchangers or geothermal probe systems that are installed in shafts and tunnels and, if necessary, in connected sections of the mine workings. In the pipe heat exchangers made of metal or plastic (e.g. PE), a heat transfer medium circulates which absorbs the heat from the mine water or the mine structure. It is conceivable to open up the backfilling column of a shaft via closed geothermal probes (e.g. Auguste Victoria colliery, Marl and Anna colliery, Alsdorf) or the water column in the shaft after closure of the mine via a pipe heat exchanger, which, for example, is led through a degassing pipe that is still accessible.

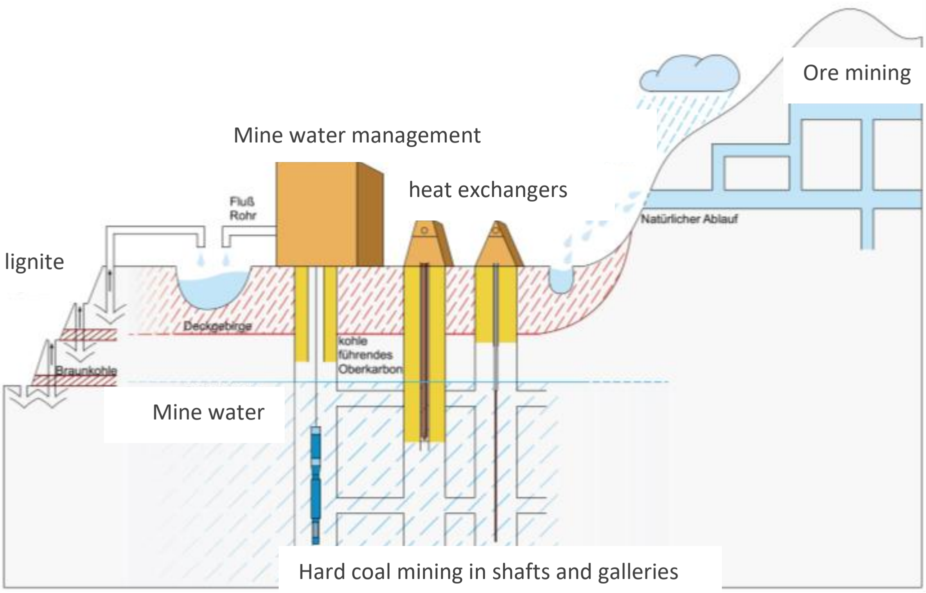

Figure 3: *Options of geothermal water production from open lignite pits, hard coal mine drainage, heat exchangers and ore mining*

Heat - directly or indirectly extracted - from the mine water can be used for heating or cooling. Exclusive direct heating is usually not possible, as the open systems use mine water from a depth of approx. 1,000 m with a maximum of approx. 35 °C and therefore often cannot provide sufficient temperatures for a low-temperature local heating network (> 60 °C). In the case of closed systems, this is accompanied by the effect that the heat transfer medium cools down considerably below the natural ambient temperatures of the shaft during long-term extraction; even if temperatures > 50 °C are reached in individual cases in shafts of up to 1,500 m. This means that in heating mode, downstream devices are required to increase the temperature in the secondary circuit by means of heat pumps. For direct cooling the initial temperatures are generally too high. Open systems with pit water close to the surface at temperatures of < 14 °C are an exception.

Plants for the use of mine water have been operated on an international and national level since the 1980s, whereby the number of active heating networks is still in the low double-digit range. A total of nine project locations have been documented in NRW and the neighbouring countries (Heerlen / NL). These are six projects in the Ruhr district (3 of which are dewatering), the existing sump water utilisation at the Hambach opencast lignite mine, the shaft heat utilisation in Alsdorf (Aachen district) and the Mijnwater district heating project in Heerlen (NL).

In some of the projects, closed mines have already been drilled from above ground, such as the Mijnwater Heerlen project and the planned Dannenbaum colliery heat / cold storage project in Bochum. For this purpose, the already completely flooded and no longer accessible mine will be developed with directional drilling technology and bi-directional heat and cold utilisation of the mine water from different levels of the mine will take place with the use of large heat pumps.

Figure 4: *Project locations for mine water use in North Rhine-Westphalia and Heerlen (NL); (modified from district government of Arnsberg, 2016). Legend: O- sump pit drainage, in service; ▲- borehole heat exchanger, in planning stage; ▲- borehole heat exchanger, in service; ▼- heat storage, in planning stage; × - mine water drainage, inoperative; × - mine water drainage, in service*

Within the framework of a mine water potential study for the Environmental Protection Agency of North-Rhine Westphalia, 11 sites were identified where mine water systems for several mines are to be combined centrally and which, due to the general conditions (location of the site, hydrographs and temporal course of the pumped water quantities and water temperatures) appear suitable for the energetic use of the mine water. Eight of the sites are the central water retention systems of the hard coal mining industry, which will be continued within the framework of the eternity tasks of RAG from now on after the closure of the mining industry. Six sites (Heinrich, Robert Müser, Friedlicher Nachbar, Haus Aden, Walsum and Lohberg) are located in the Ruhr district and two others (Ostfeld and Westfeld) in the Ibbenburen district. In addition, there are the two sites Hambach and Garzweiler in the Rhenish lignite mining area, where RWE Power AG drains the ground water level, as well as the water outlet from the former Meggen ore mine.

At a central water drainage system in the hard coal mining industry (Robert Muser colliery in Bochum), 10% of the approx. 10 million m^3 of mine water (20°C) extracted per year is already being used to supply a small pilot network (two schools and Bochum main fire station).

One way for improving the energetic efficiency is to significantly increase the water temperatures by storing seasonal heat in the mines. The existing shafts and underground galleries offer excellent infrastructural conditions for the installation of seasonal heat storage facilities. Due to the large dimensions of 10 to >100 km² per colliery, depths of max. 1,200 m, rock temperatures of up to 45°C and extensive hydraulic insulation against each other, the collieries also have a considerable storage volume for excess heat from fossil power plants and industrial production processes. By heating the mine water cyclically by 30 – 50 K, it is also be possible, for example, to smooth out excess heat from electricity generation driven CHPs for the district heating networks during the summer months. Assuming an average mining volume of approx. 10 million m³ per colliery and a conservatively estimated residual porosity of at least 5% in the crushed and backfilled sections, this results in a pit water volume of approx. 0.5 - 1 million m³ per colliery. At a storage temperature of approx. 80-100 °C and a usable dT of approx. 30 - 50 K, for example, a usable heat energy of approx. 17 - 29 GWh would result. The typical seasonal storage capacity in a typical mine sector is approx. 4 - 6.6 MWth.

The projects HeatStore (Markgraf 2 Colliery, Bochum), Geo-MTES - Mine Thermal Energy Storage (Prosper Haniel Mine, Bottrop) and GRUBO - Mine Heat Bochum (Dannenbaum Mine and Prince Regent Mine, Bochum) are currently investigating the storage potential of underground coal mine infrastructures.

Objectives are, among others, the following:
- Identification and testing of new, cost-effective materials, insulations and construction principles for seasonal underground heat storage;
- Improvement of storage density with innovative materials and heat carriers;
- Optimization of seasonal storage concepts for heating and cooling applications in large building complexes and new urban areas;
- Connection to existing district heating networks;
- Improvement of the energy efficiency of electric cogeneration and heat extraction in district heating plants.

The total mining area on Prosper Haniel is 165 km² and the underground road network has a length of 151 km at a maximum depth of more than 1200 m with more than 40°C. The mining area of Prosper Haniel is located in the south of Germany. Assuming that only 1% of these areas can be used for heat storage in a formation thickness of 100m, the total storage capacity is approx. 100 GWh/K.

Added value for the heat mining industry

The geothermal industry has multiple structural similarities to the conventional mining industry. The added value of geothermal energy technologies is generated a) for different applications (heating, cooling, power generation) and b) in different output ranges (from the heat supply of a detached house to large municipal plants with thermal and / or electrical outputs in the MW range). The geothermal market can be divided into 12 sectors. These cover in their entirety all industries and services that are provided during the construction and operation of a geothermal plant. In the Ruhr area alone it is assumed that at least 300 companies with approx. 4,000-5,000 employees are active on the geothermal market; nationwide this is approx. 20,300 with an investment volume of EUR 1.3 billion (2017).

The geothermal industry in most European countries has only developed perceptibly since the turn of the millennium on two pillars: a) young companies that were founded explicitly for the new market and b) established companies in geotechnics, mining and energy technology that adapt their portfolio to a changing need as they move away from large, centralised fossil fuel-based producers to smaller, decentralised plants. In Germany the largest share - not least due to a market growth of more than 9,200 geothermal heat pump systems per year (2017; BWP) - is accounted for by the sector of plant construction for heating and air-conditioning technology with 39% of all companies, followed by engineering, planning and exploration companies with 18%. The remaining 8 sectors account for single-digit percentages.

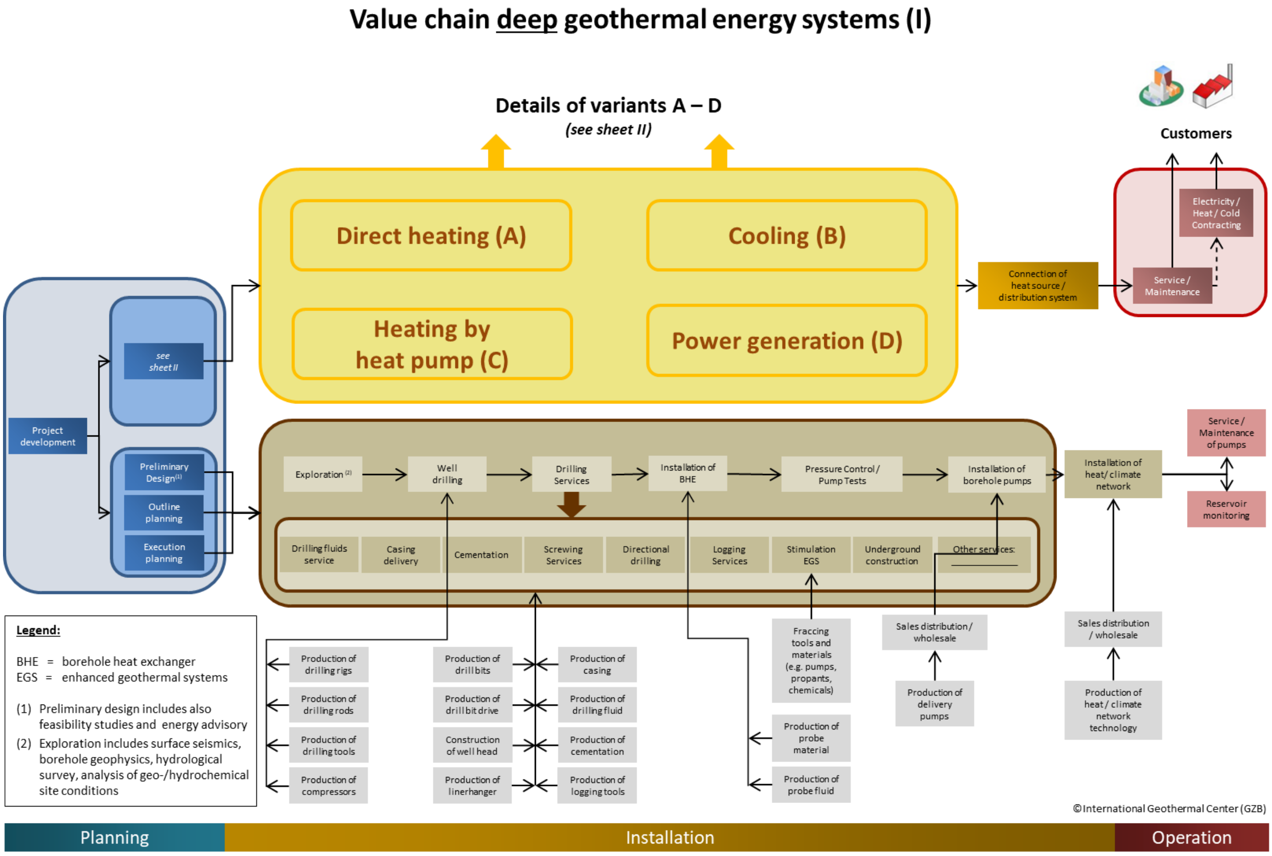

***Figure 5**: Added value chain of the geothermal industry (subsurface part).*

The size structure of the geothermal industry is also heterogeneous: around 15-20% are globally active industrial companies with services and products for heating, cooling, power plant and mining technologies. Some of them are among the world market leaders - e.g. in cooling technology for geothermal power plants. However, the majority of market participants tend to be small to medium-sized. It can be assumed that about half of the companies with up to 20 employees achieve annual sales of up to EUR 5 million on the geothermal market. About one fifth of these companies are active in two or more of these sectors.

Most companies have entered the still young market within the past 15 years (from 2003). As a rule, these are not newly founded companies, but rather the expansion of a traditional business field to include geothermal products, e.g. from drilling and pumping engineering (10 %), district heating (7 %) and power plant technology (4 %).

Conclusions

The European energy infrastructure needs to be transferred from CO_2-emitting fossil fuels to renewable sources. This transition process from coal mining to heat mining brings an enormous potential for the former mining regions in Europe. Not only by using the existing underground mining infrastructure and mine waters for heat production and storage – moreover, the mining industry has the chance to re-invent itself in the upcoming years.

The current state of research suggests, that under the currently determined boundary conditions a technical realization of the mine water utilization for heating and cooling in the abandoned collieries is possible by using directional drilling and implementation of low-ex grids. Results of the numerical thermal-hydraulic simulations for several coal mines show that the flooded mine reservoir on the basis of the selected thermal and hydraulic conditions of the subsurface, the determined demand of energy and the temperature distribution in the planned supply grid sustainably provide the heat and cold volumes over a period of 50 a.

With regard to energy consumption in Germany for example, it is noticeable that the largest share goes into heat consumption. Final energy consumption in 2017 was 9,329 petajoules (that is 2,591 billion kilowatt hours). Of these, 54% alone account for the heat share. The majority of borehole, production, heat conversion and distribution technologies are well developed. Or they can easily be transferred from coal to heat. A whole variety of support and promotion mechanisms – such as risk mitigation funds for smaller utilities and municipalities - should politically leverage the transformation of the European heating sector. Geothermal energy clearly has the potential to become the key component of the heat conversion. In combination with heat pumps and other renewable energies, for example for power of the pumps or in combination with thermal storage or cooling, there is an enormous development potential for the mid-depth geothermal energy. The individual technologies are market-ready and many of them have their roots in the conventional mining industry.

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