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The Energy Transition from Fossil Fuels to Geothermal Energy – a German Case Study

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ABSTRACT

With the stipulated phase-out of nuclear power by 2023 and coal by 2038, Germany is one of the worldwide biggest technology-based populations on its way from fossil fuels to renewable energies. The renewable energy act from 2000, adjusted several times, induced the growth of the share of renewable energy (RE share). In 2017, final energy consumption in Germany was 9,329 petajoules (corresponding to 2,591 billion kilowatt hours) whereof 54% account for the heat share.

According to the schedule of German Renewable Energy Sources Act (EEG) the RE share in gross electricity consumption shall increase at least 35% by 2020. This goal has already been achieved. In 2018, renewable energies accounted for 38.2% of gross electricity consumption, more than doubling their share since 2010 (17.0%).

The situation is different for the share of renewable energies in heat consumption, although this accounts for the greater part of final energy consumption in Germany. The RE share on heat grew unsteadily and even dropped from 2012 to 2018 to 13.9% (Fig. 3) (target of EEG or EU is 14%). In 2018, the RE share in power and heat has so far accounted for only 16.7% of gross final energy consumption. At the moment biomass accounts for the largest contribution to renewable heat with almost 86%. However, due to its high space requirements and other environmental influences, it has only limited potential for expansion.

The heating sector covers the largest portion of the primary energy consumption in Germany. Fossil fuels such as coal, oil and natural gas used hitherto for space heating can be substituted by geothermal energy due its low space requirements and scalable application opportunities. Due to the federal system in Germany, the political efforts to implement geothermal energy varies from state to state. Two examples of different energy needs and strategies to implement geothermal energy are presented: One example is the state North Rhine Westphalia, where the largest district heating net is located and the federal government envisages geothermal energy as major contributor to decarbonize this heating grid. Exploration and technology development has already started, however deep geothermal energy is not developed yet. Another example is the city of Munich in Bavaria, which aims as the first major German city to provide 100% of the district heating from renewable energies by 2040.

Generally spoken, there is still a large potential for expansion through the utilisation of ground source heat pumps, especially for new buildings. In addition, in the next few years many outdated heaters must be replaced in the private sector. With already more than 382,000 installed systems in Germany, ground source heat pumps are a widespread, successful and affordable technology.

The strength of geothermal energy lies in its scalability and efficiency with a wide range of applicable technologies and possibilities – depending on depth and end use. The case study Germany demonstrates that energy transition and climate protection can only be achieved with a heat transition, i.e. decarbonisation of heating facilities on all scales.

1. INTRODUCTION: ENERGY TRANSITION IN GERMANY

One of the most well-known German laws worldwide is the law for the extension of renewable energies named the Renewable Energy Sources Act (short title renewable energy law, EEG). This law came into force in 2000 and was amended on different levels in 2004, 2009, 2012, 2014 and 2016/2017. The predecessor of the EEG is the Law on the Feed-in of Electricity from Renewable Energies into the Public Grid - the Electricity Supply Act – enforced in 1990, the world's first green electricity feed-in law. Based on this history, the early versions of the EEG focused on electricity and aimed to regulate the preferred feed-in of electricity from renewable sources into the power grid by guarantees their producers fixed feed-in tariffs. The Working Group on Renewable Energy Statistics (AGEE-Stat) statistically reviews the development of the share of renewable energies in Germany, the Geothermal Information System of Germany, developed by the Leibniz Institute for Applied Geophysics and funded by the Energy Research Program of the Federal Ministry of Energy BMWi, provides the national statistics of geothermal installations into the AGEE.

Since the enforcement of the EEG, the renewable energy (RE) share on the primary energy consumption grew steadily from 2.9% in 2000 to 14% in 2018 (Fig. 1), equivalent to 16.7% of the gross energy consumption. The energy target of the European Union to cover 20 % of the gross energy consumption by RE in 2023 seems therefore affordable for Germany. Reviewing the energy sectors in Germany, the results looks different: while the RE share on electricity grew steadily to 38.2% in 2018 (Fig. 2) (target of EEG or EU is 35%), the RE share on heat grew unsteadily and even dropped from 2012 to 2018 to 13.9% (Fig. 3) (target of EEG or EU is 14%). The major share of the primary energy consumption in Germany is, however, heat (Fig. 4). The current recognition is that the achievement of climate protection goals and a successful energy transition, referred as *"Energiewende"* in German, is based on a successful heat transition, referred as *"Wärmewende"*. This situation raises the question how to cover this current and future need in heat, particularly in times of the stipulated phase-out of nuclear power by 2023 and coal by 2038, and how geothermal energy can be implemented into the heat energy provision.

The majority of geothermal projects worldwide are located in geological systems with convection dominated heat transport such as magmatic arcs or large-scale active faults (e.g. plate boundaries) (Moeck, 2014). Germany, with its conduction dominated heat transport systems, lacks natural steam reservoirs, which are functional for a direct drive of turbines (Moeck, 2014). Thus, geothermal power generation in Germany operates with binary systems, which use a working fluid in a secondary cycle (ORC or Kalina cycle). At the end of July 2019, ten geothermal plants with an installed capacity of about 43 MWel feed electricity into the German grid. In the heating sector, biomass accounts for the largest contribution to renewable heat with almost 86% in Germany (Fig. 5). However, due to high space requirements and other environmental influences, agriculture for biomass has a limited potential for expansion. In addition, waste combustion is already efficiently used as heat provision with no significant expansion potential. Geothermal energy as major source for a future renewable heat provision seems therefore physically and economically logic. In the past, deep geothermal energy was often thought of as generating electricity from geothermal energy, forced by the feed-in tariff of the EEG. But now - in the run-up to the heat conversion - the geothermal energy in its whole range seems much more useful for the heat supply.

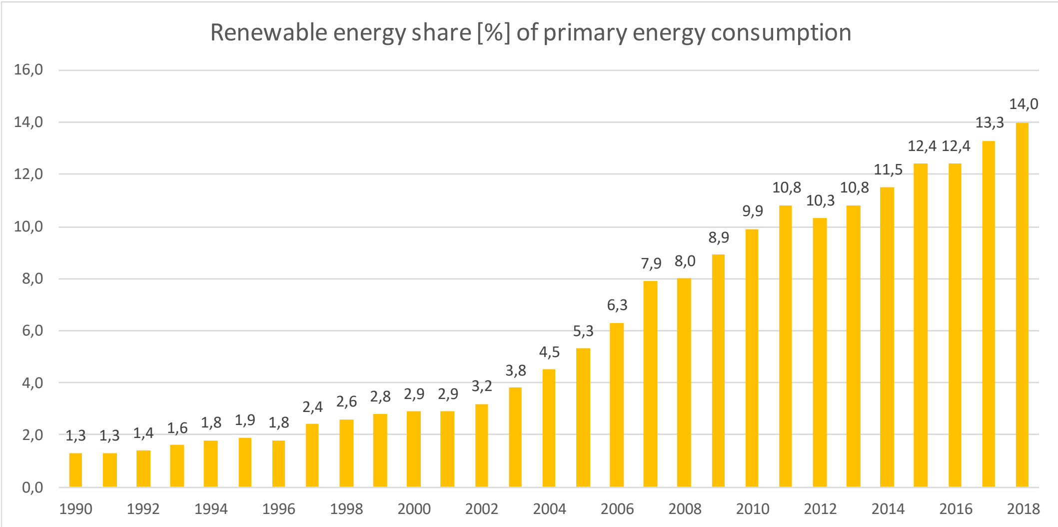

Figure 1: Development of the renewable energy share of the primary energy consumption in Germany (after BMWi (2019) based on Working Group on Renewable Energy-Statistics (AGEE-Stat); as of February 2019; all figures provisional).

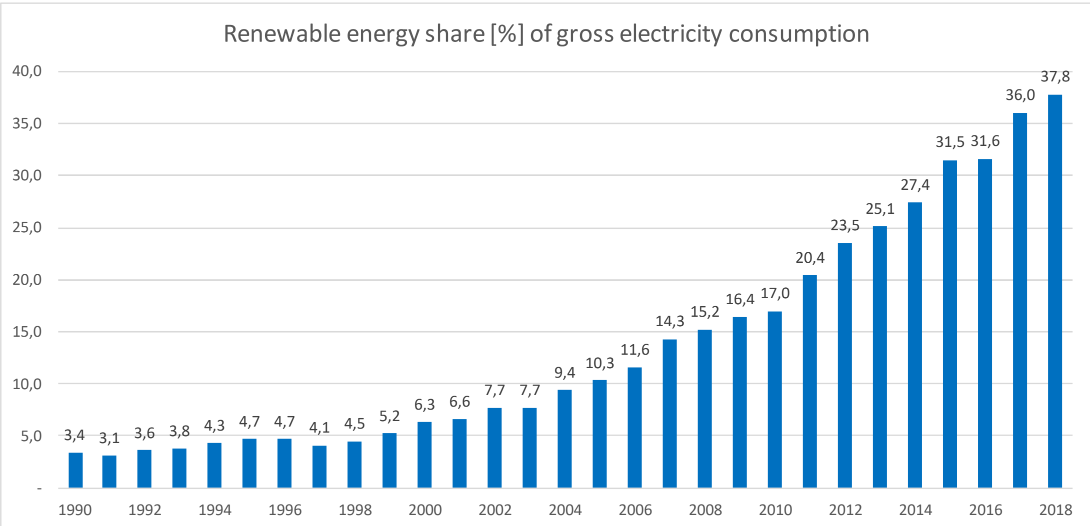

Figure 2: Development of the renewable energy share of gross electricity consumption in Germany (after BMWi (2019) based on Working Group on Renewable Energy-Statistics (AGEE-Stat); as of February 2019; all figures provisional).

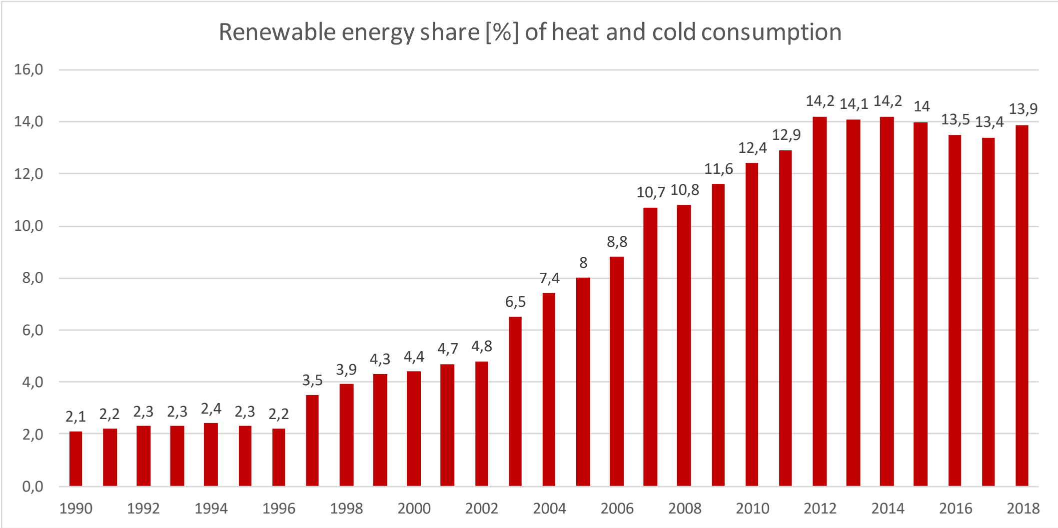

Figure 3: Development of renewables-based heat and cold consumption in Germany (after BMWi (2019) based on Working Group on Renewable Energy-Statistics (AGEE-Stat); as of February 2019; all figures provisional).

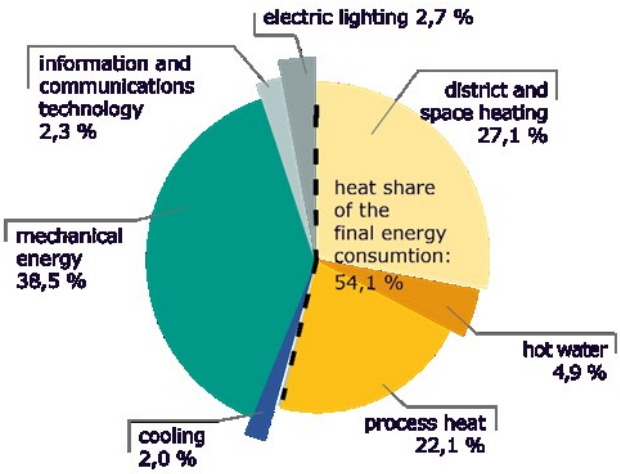

Figure 4: Sections of the final energy consumption in Germany (from Weber & Moeck, 2019; after BMWi (2019) based on Working Group on Renewable Energy-Statistics (AGEE-Stat); as of February 2019; all figures provisional).

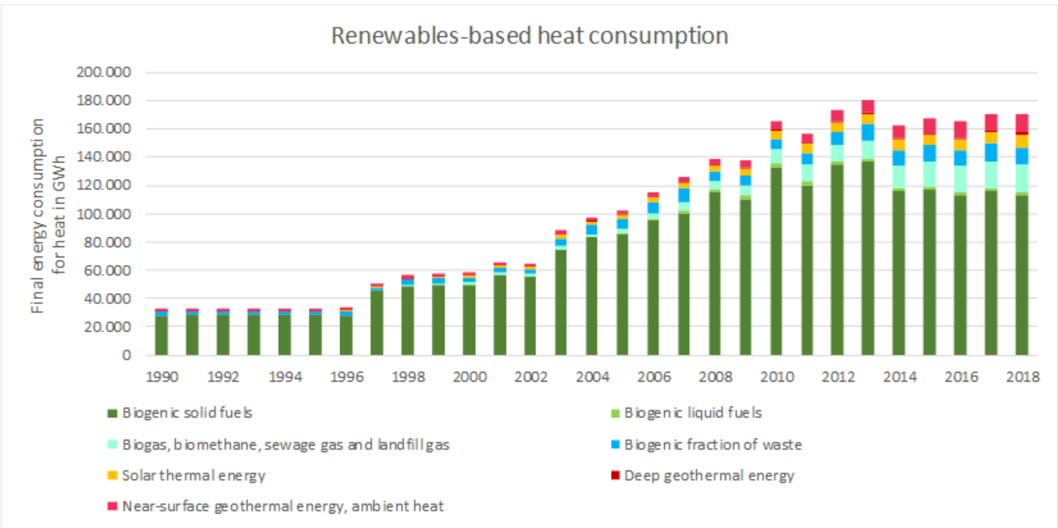

Figure 5: Development of renewables-based heat consumption in Germany (after BMWi (2019) based on Working Group on Renewable Energy-Statistics (AGEE-Stat); as of February 2019; all figures provisional).

2. THE ROLE OF GEOTHERMAL ENERGY IN RENEWABLE ENERGY PROVISION

Over the last 10 years, geothermal energy in Germany has experienced an enormous increase in development. The geothermal installed capacity of direct heat use applications shows a considerable increase from 157.8 MWth in 2010 to 336.1 MWth in 2015 and reached 406.3 MWth in 2018 (GeotIS, 2019; Agemar et al., 2014). 26 district-heating and combined heat-power plants cover the largest portion of the geothermal capacity with about 346 MWth. Most of the geothermal district heating and power plants are located in the Molasse Basin in southern Germany, due to favourable geological conditions in carbonate rock in 2,000 to 5,000 m depth. Additionally, in the North German Basin new developments as the municipal project Schwerin utilize sandstone successions in 1,000 to 2,500 m depth, combined with a high-temperature heat pump. Particularly, mid-deep reservoirs are considered as plays with high economic potential specifically for district heating because drilling costs are lower compared to deep reservoir access, and – combined with high-temperature heat pumps – are flexible in heat provision. The only geothermal play province with convection dominated heat transport is the fault controlled Upper Rhine Graben, where a number of geothermal project are developed or under current development (Agemar et al., 2014).

Common deep geothermal utilisations for direct use are district heating plants or combined heat and power plants (CHP), thermal spas, and space heating. In addition, at Kirchweidach (Bavaria), a greenhouse is served by geothermal energy to substitute fossil fuels for heating. At present, about 190 geothermal installations of these types in a depth range between 400 and 5,000 m are in operation in Germany (Fig. 6).

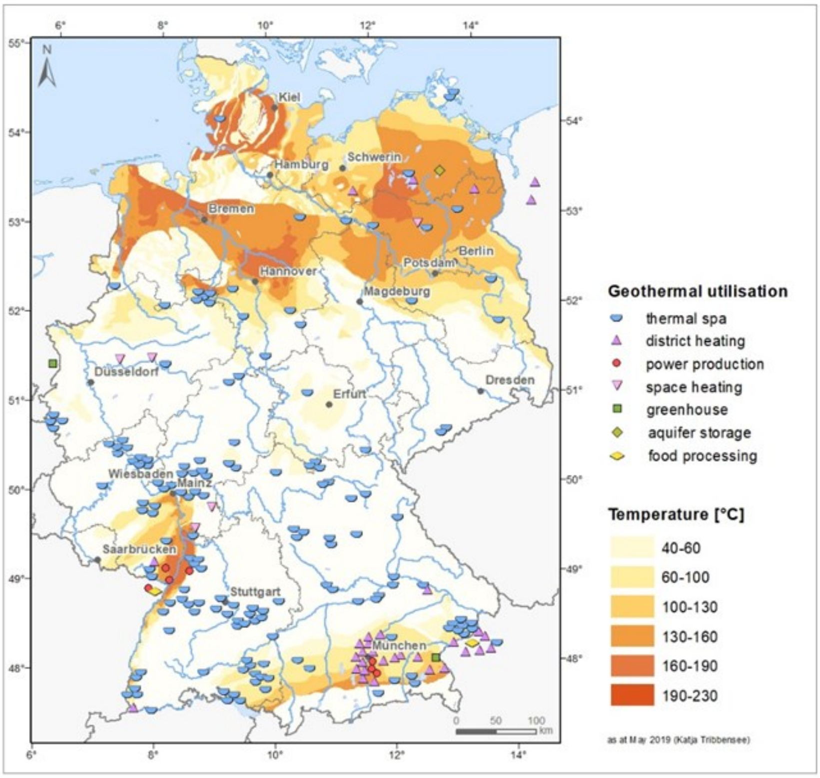

Figure 6: Sites of deep geothermal utilization in Germany and neighboring countries. The background colors represent predicted temperature ranges of the respectively deepest identified geothermal resources in sedimentary or volcanic rocks (map generated in GeotIS, 2019).

Geothermal well doublets consisting of a production and an injection well are typically used for district heating, while spas only need a single well for standard operation. Furthermore, five medium-deep to deep borehole heat exchangers are in operation in Germany. In addition, the use of mine water is becoming more and more interesting with regard to the heat transition in Germany.

In addition to installations using geothermal energy from a greater depth range between 400 and 5,000 m, numerous small- and medium-sized decentralised geothermal heat pump units are in use for heating and cooling of individual houses and office buildings. At the end of 2018, more than 380,000 geothermal heat pumps were running successfully in Germany and supply renewable heat mostly for residential buildings. At the end of 2018, installed geothermal heat pumps have reached a thermal output of about 4,400 MWth in total (Weber et al., 2019).

A whole variety of federal support programs shall help to leverage the transformation of the heating sector, partly focusing specifically on geothermal energy for homeowners, companies or municipalities. For the R&D sector, it is the seventh Energy Research Program of the BMWi with an annual budget of some tens of Million Euros, and several singular strategic support lines as the current program Living Labs for Energy Transition with a one-time budget of 100 Million Euros. For the private, commercial and municipal sectors, several incentive programs exist: e.g. for the energetic building restauration, leverage funding for energetic consultations, credit accommodation, subsidies for green heating or the market support program *Marktanreizprogramm-MAP* for heating with renewables, where e.g. ground source heat pumps (e.g. up to 4.500 Euros for private persons; up to 100,000 Euros per facility for companies; up to 100,000 Euros amortisation grants for municipalities) or drilling costs for wells deeper than 400 m are significantly leveraged.

3. EXAMPLE FOR TRADITIONAL COAL MINING DISTRICT: DEEP GEOTHERMAL ENERGY IN THE RHINE-RUHR REGION (RRR)

The Rhine-Ruhr Metropolitan Region (RRR), with a population of around ten million, is one of the three largest conurbations in Europe, alongside Paris and London; more than 5 million people live in the Ruhr alone. Based on the major 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) (Fig. 7). The connection of the Ruhr network with the district heating network of the Lower Rhine Region (620 km, 844 MWth, 981 GWh/a) between Duisburg and Bottrop leads to the largest combined heat and power network in Europe from 2020.

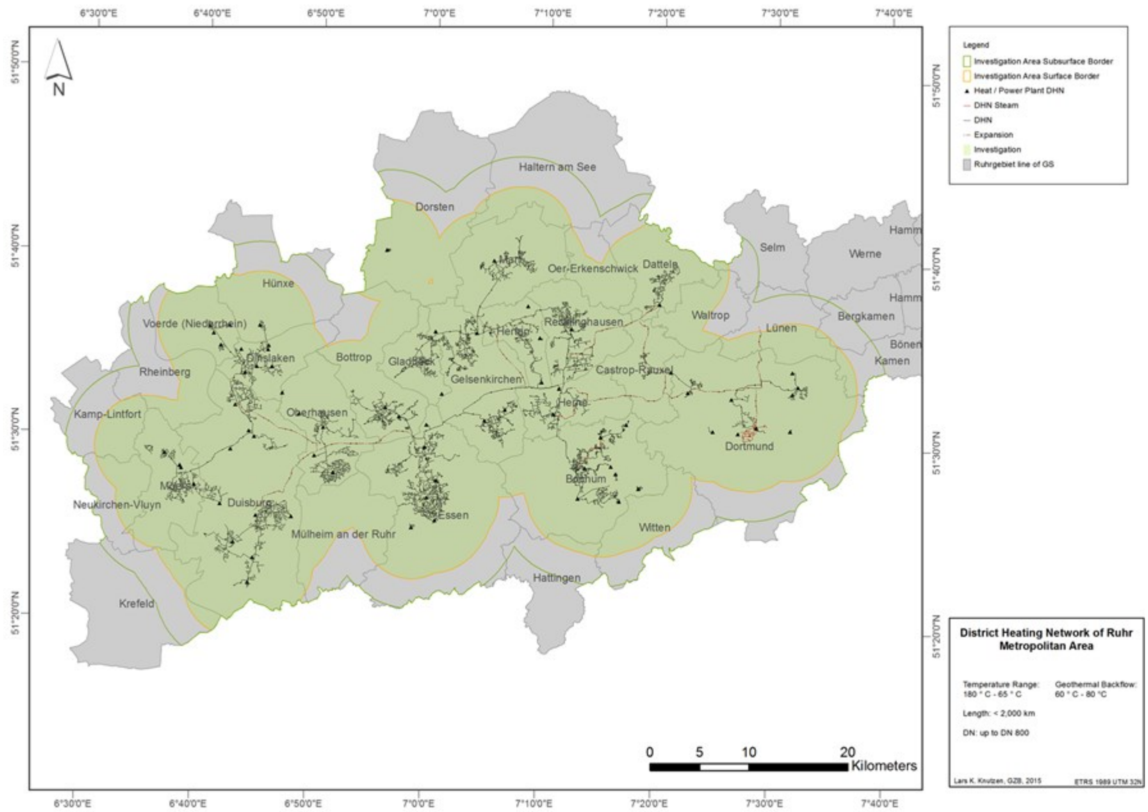

Figure 7: Ruhr heat network with fossil heat generation plants.

Efforts to convert the district heating systems of the Rhine-Ruhr Region are aimed at this end:

- Replacing older fossil-fuel power plants with new, efficient renewable energy plants
- Gradual reduction of the flow 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 focuses on two topics: a) conventional hydrothermal reservoirs in pre-fractured 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 as well as karstified limestones and dolomites. The carbonate rocks of the Devonian (especially mass limestones of the Middle Devonian) were deposited in all NW-Europe in lagoon areas of the Rheno-hercynian shelf between reef bodies and mainland (Fig. 8). They outcrop from the Ardennes mountains in Belgium (e.g. at the „original“ balneogical town Spa), via the Northern Eifel near Aachen, the Rhenish (Variscian) mountains and in the Sauerland. In the Wuppertal area they are mined at surface with thicknesses of approx. 300 – 500 m. From there they follow the general stratification in the direction of the North German basin. In the deeper underground of the Lower Rhine Basin as well as in the Ruhr Valley area, limited statements on the distribution between 3000-7000 m via deep boreholes in the Lower Rhine and the Muensterland #1 borehole are possible. Carbonates of the Lower Carboniferous are deposited above the Devonian mass limestones, referred as *Massenkalk* (Fig. 8). They are divided into two large sedimentation areas. These include the Kohlenkalk (coal-limestone) facies SW 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 Kulm facies in the eastern Ruhr area and Westphalia with calcareous deep-sea deposits (Calciturbidites / Platecarbonates) thicknesses of 200 m are assumed. Outcrops on the Lower Rhine already show karstification up to 1,000 m thickness. North of the RRR massive limestones of cretaceous age will be found at medium depths to ca. 2000 m.

In addition to the carbonates, potential hydrothermal reservoir rocks in NRW are Ruhr sandstone (e.g. Kaisberg, Grauwacke) 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 Münsterland. Due to the rather low porosities, hydrothermal circulation in the area of tectonic faults or in extensional tectonic fold / fracture structures may be considered.

In Aachen, the Romans have used hot waters from the Devonian limestones since the 1st Century for the operation of the first geothermal district heating system north of the Alps and now – 2000 years later – the City has implemented again a small 2.5 MWth hydrothermal network. Within the EU Interreg DGE Rollout project, the aim is to go back to the roots and replace 85 MWth from lignite combustion by geothermal energy.

The total geothermal potential of these formations in the Ruhr Metropolitan area is approx. 92,300 GWh/a (of which Devonian mass limestone: 59,200 GWh/a; Kulm / Kohlenkalk Lower Carboniferous: 10,400 GWh/a; Graywacke Namur B / Upper Carboniferous Oberkarbon: 22,700 GWh/a). This means that the potential exceeds the required amount of heat in the district heating network Ruhr by a factor of more than 10-20 - depending on the expansion scenario. A very rough estimate would theoretically require 150 to 200 geothermal heating plants to provide the heat. In order to secure this still very abstract approach, an investigation programme is planned for the creation of a valid data situation. As an example for the Rhine-Ruhr Region, the existing Bochum-Sued district heating network (115 MWth) shall be converted from natural gas to deep geothermal energy within the umbrella project TRUDI. The objective of TRUDI is a) the development of the necessary geoscientific and energy-technical decision bases for the energy industry in total NRW. The geological objectives of TRUDI are hydrothermal reservoir characterisation at depths of 4000-5000m within the folded sedimentary reservoir rocks of the Variscan basement and medium-deep reservoirs to 1000 m for seasonal heat storage in the remaining subsurface infrastructures of the hard coal mines.

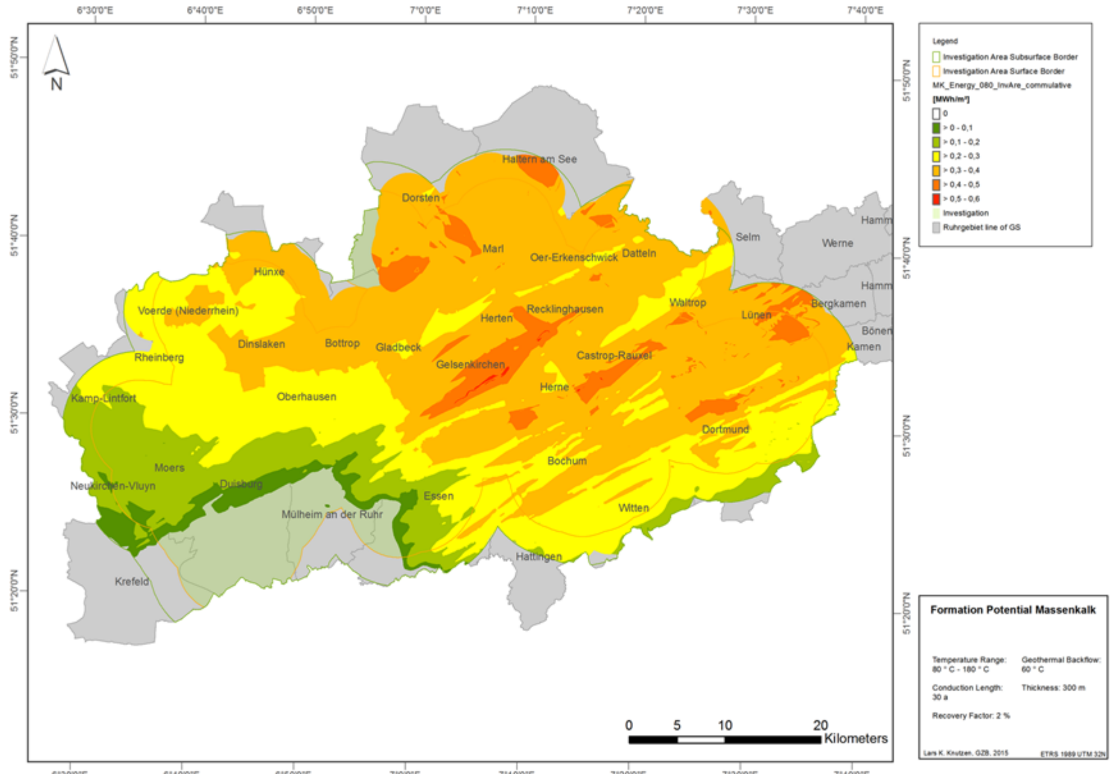

Figure 8: Geothermal potential of Devonian limestone referred as *Massenkalk* with more than 300 m thickness, in 3,000 to 7,000 m depth, in temperature range of 80°-180°C (after Bracke et al., 2016)

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

The State of North Rhine-Westphalia was historically 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 the German hard coal mining in the mid-1950s, more than 200 mines were in operation between Alsdorf nearby the Dutch border, Kamp-Lintfort on the Lower Rhine, and Hamm in Westphalia. With the closure of the last colliery Prosper Haniel at the end of 2018, the coal industry at the Rhine and Ruhr is history. Subsequently, the mine water drainage at > 1000 m in the region with approx. 100 million m3/a will be reduced to a controlled level of 300 - 500 m below ground level, in order to prevent mixing-ups of drinkable ground water with mine waters of high salinity.

However, the mine structures that are no longer used offer an enormous potential for grid-connected heat supply (Fig. 9). In addition to the direct energetic use of mine water, seasonal heat 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 draining measures in open-cast mines, whereby the mine water is actively pumped and discharged into an above-ground receiving watercourse.

In open well systems, the mine water is extracted from the underground mine infrastructures exclusively for energetic purposes and returned to the mine elsewhere. In this case, open shafts or directional boreholes, which target 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) 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.

The 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 mine water from a depth of approx. 1,000 m with a maximum of approx. 35 °C and therefore cannot provide sufficient temperatures for a low-temperature local heating network (approx. 50 °C). This means that in the case of heating, downstream devices are required to increase the temperature in the secondary circuit by means of heat pumps. The initial temperatures are generally too high for direct cooling. 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. Nine project locations have been documented in NRW and the neighbouring countries (Heerlen / NL). These are six projects in the Ruhr Valley Region (3 of which are dewatering: Robert-Mueser, Bochum; Zollverein, Essen; Markgraf 2, Bochum), the existing sump water utilisation at the Hambach opencast mine, the planned shaft heat utilisation in Alsdorf (Aachen) 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 heat/cold storage project (former Opel site, Bochum). For this purpose, the already completely flooded and no longer accessible mine will be developed with directional drilling technology and the mine water will be used for bi-directional heating and cooling from different levels of the mine using large heat pumps.

Within the framework of a mine water potential study for the LANUV NRW, 11 sites were identified where water-dewatering systems for several mines are to be combined centrally. 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 after 2018 - the closure of the mining industry. Six sites (Heinrich, Robert Müser, Friedlicher Nachbar, Haus Aden, Walsum and Lohberg) are located in the Ruhr Valley and two more (Ostfeld and Westfeld) in the Ibbenbüren district. In addition, there are the two sites Hambach and Garzweiler in the Rhenish lignite mining area.

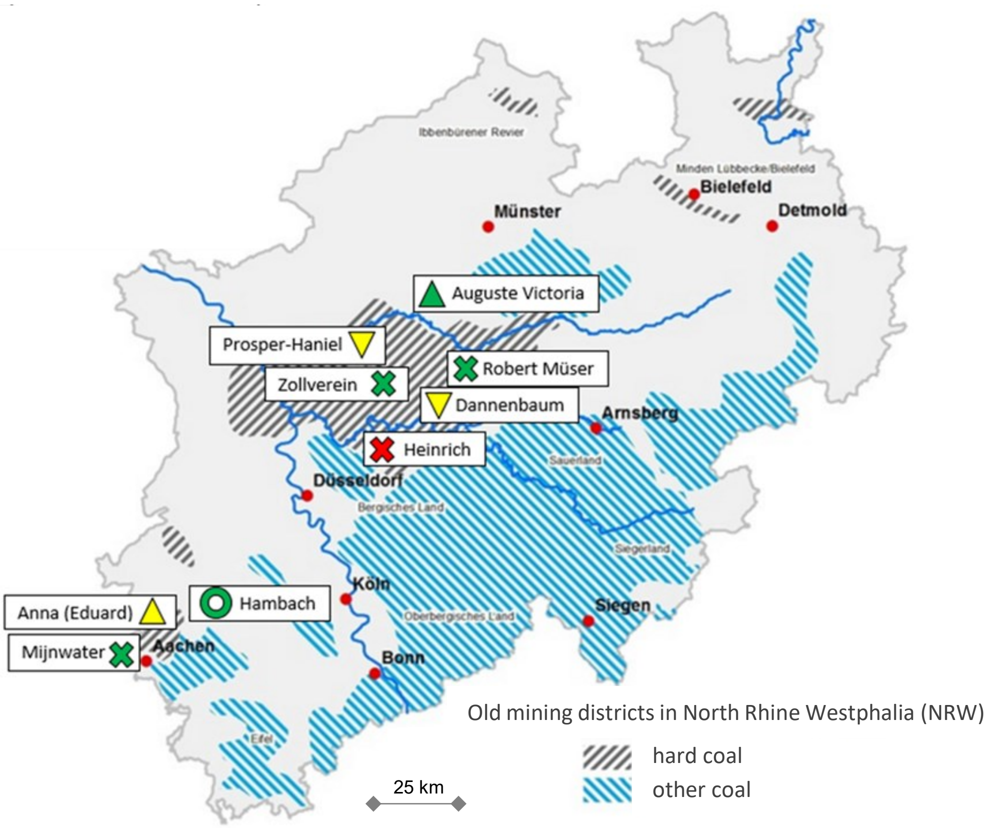

Figure 9: Project locations for mine water use in NRW and Heerlen (modified from district government of Arnsberg, 2016). Legend: ○ - sump pit drainage, in service; △ - borehole heat exchanger, in planning stage; ▲ - borehole heat exchanger, in service; ▽ - heat storage, in planning stage; × - mine water drainage, inoperative; × - mine water drainage, in service

At a central water drainage system in the hard coal mining industry (Robert Mueser colliery in Bochum), approx. 10% of the approximately 10 million m3 of mine water (20°C) pumped per year is already being used to supply a small pilot network (two schools and Bochum main fire station).

One way of increasing efficiency is to significantly increase the mine 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 up the mine water cyclically by 30-50K, it would also be possible, for example, to smooth out excess heat from current-controlled CHPs for the district heating networks in the summer months. Assuming an average overburden 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 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 mine buildings (Fig. 9). Objectives are, among others, the connection to existing district heating networks and improvement of the energy efficiency of electric cogeneration and heat extraction in district heating plants.

4. EXAMPLE FOR METROPOLITAN REGION: MUNICH

The most widely developed conductive geothermal play province in the world is the Bavarian Molasse Basin (Fig. 6). The Molasse Basin is a foreland basin characterized by the asymmetric basin shape with the greatest depth directly in front of the mountain front. This situation combined with a partly permeable carbonate reservoir rock that allows circulation of thermal water or formation fluids in general is optimal for the formation of geothermal resources. In Bavaria, the existing customer structure for heat combined with the political framework conditions promoted by the EEG (*Erneuerbare Energien Gesetz*, i.e. renewable energy law) promoted the basin-wide development of the Molasse Basin as the world's first geothermally used foreland basin among geothermal reservoir types. The exploration of the Mesozoic carbonates began in the 1970s for groundwater development. Tectonic and sedimentary cycles causing variable reservoir permeability have been recorded and described (Lemcke, 1976; Bachmann et al., 1987). The 3-5 km deep formation of the Upper Jurassic was initially explored as a hydrocarbon reservoir and for about 15 years as a geothermal resource. As a carbonate formation, the Upper Jurassic is a typical fracture controlled reservoir, which can be strongly influenced by solution processes (karst), rock formation and pressure-solution processes (diagenesis) or deposits (facies) in its storage quality.

The geothermal development started in 1998 in the greater Munich area and significantly grew from 2004 on obviously stimulated by the EEG. While power production was in the focus of geothermal developments in the 2000s, today heat and district heating is in the focus of geothermal development in Germany. Effectively, the first geothermal power project Unterhaching, starting with power generation in 2008, ceased its power production in 2018 and provides heat for the expanding municipal district heating grid only. There are currently 33 permit fields in Bavaria for commercial or large-scale exploration of geothermal energy of which 26 fields are developed and under production. 58 deep wells have been drilled or are used for geothermal development in the Malm (Fig. 6). Of the 58 holes, four wells are economically non-productive (updated from Moeck & Zimmer, 2014).

Deep geothermal energy plays a key role for the city of Munich due to the favourable geological subsurface conditions. The municipal energy provider Stadtwerke München SWM is currently on its way to transform its energy provision from fossil fuels to renewable energy and has started this process in 2008 (Jahrfeld, 2018). The green vision of the SWM envisages the implementation of green electricity by 2025 and green district heating 2040. With its more than one million customers, the SWM are one the first energy provider of metropolitan city that enforces the energy transition in Germany, specifically by integration of geothermal energy for district heating by more than 800 km grid length. In 2019, the SWM operate five well doublets with 25 WMth and 15 MWel and 0.1 TWh per year (Jahrfeld, 2018). The strategic goal for 2040 foresees 16 well doublets with an installed capacity of about 360 MWth and 2.4 TWh per year. Currently, a geothermal city site with three well doublets drilled from one drill site is under construction, with a planned installed capacity of 50 MWth (Jahrfeld, 2018). In 2016, a large 3D seismic survey covering 170 km^2 of urban area in Munich South was accompanied by applied research of the LIAG by a shear wave experiment and high resolution structural seismic interpretation (project Geoaramol). A current research project deals with borehole integrity and sustainable reservoir operation by numerical models. The modelling procedure is accompanied to the current drilling operation, well logging and testing of the SWM (project REgine). The goal of the SWM is to be the first green city metropolis in Germany, with geothermal energy as fundament for district heating.

Encouraged by the Munich energy vision, recently another metropolitan energy provider committed to green energy provision with geothermal energy as key resources for heating and cooling on different scales: Hamburg Energie envisages to provide heat from geothermal resources on the Elbe Island Wilhelmsburg as part of a holistic energy system approach. In 2019, Hamburg Energy received funding for its concept *Integrierte WärmeWende Wilhelmsburg* (i.e. integrated heat transition of Elbe Island Wilhelmsburg) from the competitive support program “living labs for the energy transition” of the BMWi. Interestingly, Hamburg is located in the North German Basin, an intracratonal basin, which is a different geothermal play type than the foreland basin, where Munich is located. While research results from Munich is relevant for foreland basin play provinces as carbonate play levels, Hamburg will be crucial for intracratonal play provinces and siliciclastic play levels.

5. POTENTIAL FOR EXPANSION FOR GEOTHERMAL ENERGY

For geothermal energy, there is an enormous potential for expansion for the heat conversion with a simultaneous low area requirement and flexible application possibilities. Fossil fuels such as coal, oil and natural gas can be substituted by geothermal energy in many areas of heat generation. An example from a Bavarian municipality shows, the expansion of geothermal heating networks enables a faster implementation of the heat cycle than the energetic renovation of existing buildings (Moeck & Kuckelkorn, 2016).

For this reason, geothermal energy should be taken into account particularly at the municipal level.

The new German perspective on geothermal energy is to consider the whole subsurface as geothermal energy source specifically for heat and storage. The new federal energy research program of the BMWi supports now geothermal projects in general and does not differ between shallow and deep geothermal projects (BMWi, 2018). From near the surface to medium deep to deep, the use of geothermal energy is possible almost everywhere for heat provision on different scales. Depending on the heat demand and the nature of the geological subsurface, various geothermal technologies are available and offer versatile application possibilities. We call this the *scalability* of geothermal energy (Fig. 10).

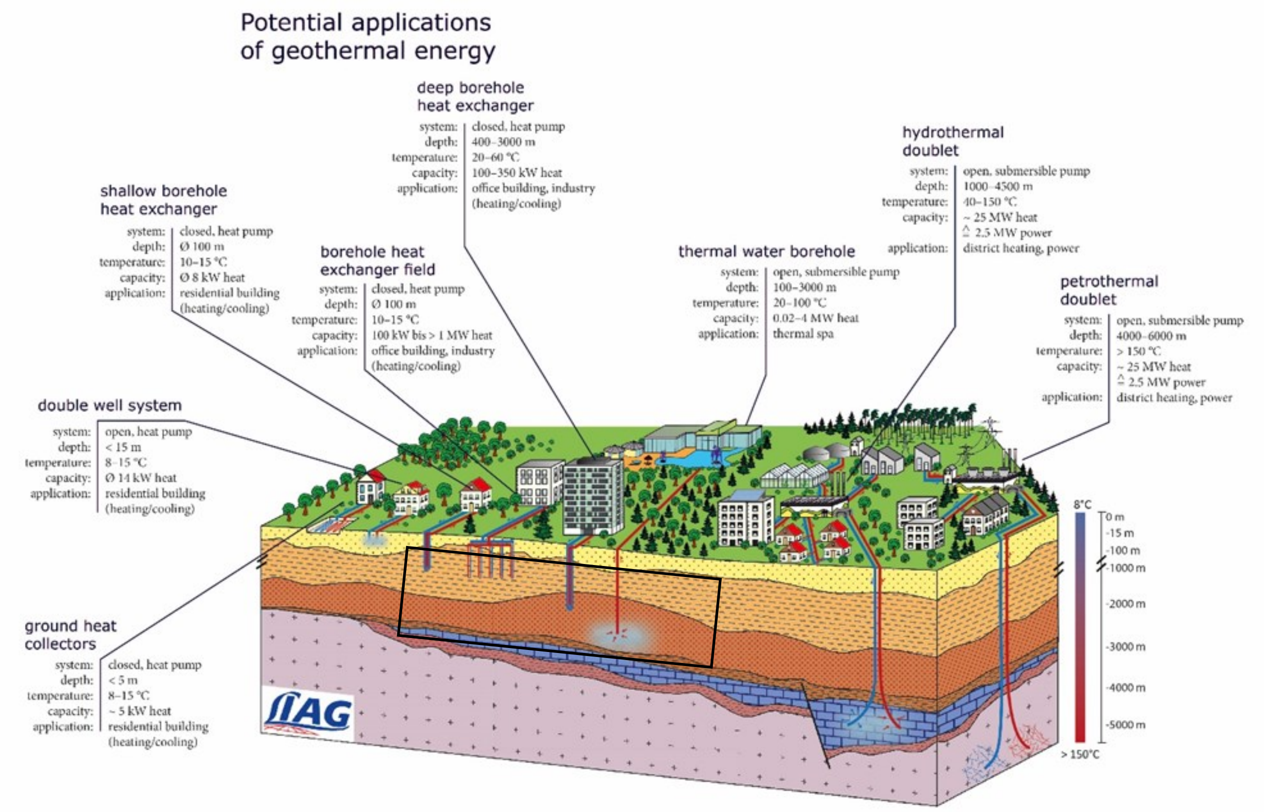

Figure 10: Range of possible geothermal applications from shallow to deep resources in a play province with conduction dominated heat transport (adopted Weber & Moeck, 2019). Black box indicates mid-deep geothermal resources and its possible applications including well dublets, appropriate for small to medium scale heat provision.

This ranges from near-surface geothermal energy for single homes, to mid-depth geothermal energy for neighbourhoods and individual districts as well as deep geothermal energy for the supply of district heating networks in entire metropolises (Fig. 10). In combination with geothermal heat and cold storage, geothermal energy also offers other uses such as air conditioning in buildings.

A central component of this range of possible application is the medium depth of geothermal energy, which represents the transition from near-surface to deep geothermal energy. This range of geothermal application is suitable for small to medium scale heat provision (Fig. 10).

In applied geothermal research one can speak of "mid-range geothermal energy", if expensive deep drilling technology is avoided. In the past, various definitions for the depth range of the mid-depth geothermal energy have been published. According to VDI Guideline 4640 (Verein Deutscher Ingenieure, 2010), near-surface geothermal energy reaches up to 400 m, which at the same time corresponds to the lower limit of the mean depths of geothermal energy. Another point that speaks in favour of this lower limit is the market incentive program. It regulates the drilling meter conveyance, which can be used between 400 m and 1,000 m. We suggest a new definition of mid-deep geothermal resources from 400 m (specific for Germany due to the incentive program for drilling) to 2,500 m because average drill rigs can achieve this depth provided there is no over-pressured gas in the overburden of the geothermal target formation (over-pressured gas enforces the use of a blow-out preventer and cost-intensive trilling technology).

The geothermal information system GeotIS contains a total of 118 geothermal plants, which provide heat from a depth between 400 and 2,400 m (Fig. 6). Four plants are mainly used for building heating, nine for the supply of district heating networks and 104 for thermal baths. In addition, a medium-depth doublet is operated as an aquifer storage. At some locations, there are also various secondary uses, e.g. most of the thermal baths utilize their geothermal energy also for heating the building. With a thermal output of approx. 110 MW, the proportion of these mid-deep plants amounts to about 30% of the output of all geothermal sites listed in GeotIS. The already mentioned aspect of base load utilization of medium-low geothermal energy is also reflected for heat provided annually. At around 650 GWh, this makes up almost 50% of all systems available in GeotIS.

6. CONCLUSION

With regard to energy consumption in Germany, it is noticeable that the largest share goes into heat consumption. Final energy consumption in Germany in 2017 was 9,329 petajoules (that is 2,591 billion kilowatt hours) (Arbeitsgemeinschaft Energiebilanzen, 2018). Of these, 54% alone account for the heat share (see Fig. 4). The major part of implementing the energy transition is therefore in the heat sector and not in the electricity. Without the heat transition from fossil fuels to renewable energy referred as *"Wärmewende"* in German, the overall energy transition cannot be achieved in Germany.A whole variety of national support and promotion mechanisms shall leverage the transformation of the heating sector, partly focusing specifically on geothermal energy for homeowners, companies or municipalities.

The potential of geothermal energy as a key component of the heat conversion lies in its scalability and the use of a nationwide existing temperature level in Germany. Here, the mean depth of geothermal energy plays a key role and includes mid-deep geothermal borehole heat exchangers for building complexes, single boreholes for spas and mid-deep well doublets for municipal heating networks. In combination with heat pumps and other renewable energies, for example for power of the pumps or in combination with thermal storage or facility cooling, there is an enormous development potential for the mid-depth geothermal energy, due to the high heat demand in Germany and the existing market-ready individual technologies.

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