ROADMAP FOR DEEP GEOTHERMAL ENERGY FOR GERMANY

Recommended Actions for Policymakers, Industry and Science for a Successful Heat Transition

Fraunhofer IEG

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GFZ Helmholtz Centre Potsdam

KIT Karlsruhe Institute of Technology

UFZ Helmholtz Centre for Environmental Research

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Recommended Actions for Policymakers, Industry and Science for a Successful Heat Transition

Strategy paper by six institutes of the Fraunhofer-Gesellschaft and the Helmholtz-Gemeinschaft

Authors

Editors:
Bracke, R.[1] ; Huenges, E.[4]

Co-Authors:
Acksel, D.[4]; Amann, F.[1]; Bremer, J.[5]; Bruhn, D.[1]; Budt, M.[2]; Bussmann, G.[1]; Görke, J.-U.[6]; Grün, G.[3]; Hahn, F.[1]; Hanßke, A.[1]; Kohl, T.[5]; Kolditz, O.[6]; Regenspurg, S.[4]; Reinsch, T.[1]; Rink, K.[6]; Sass, I.[4]; Schill, E.[5]; Schneider, C.[1]; Shao, H.[6]; Teza, D.[1]; Thien, L.[1]; Utri, M.[1] und Will, H.[3].

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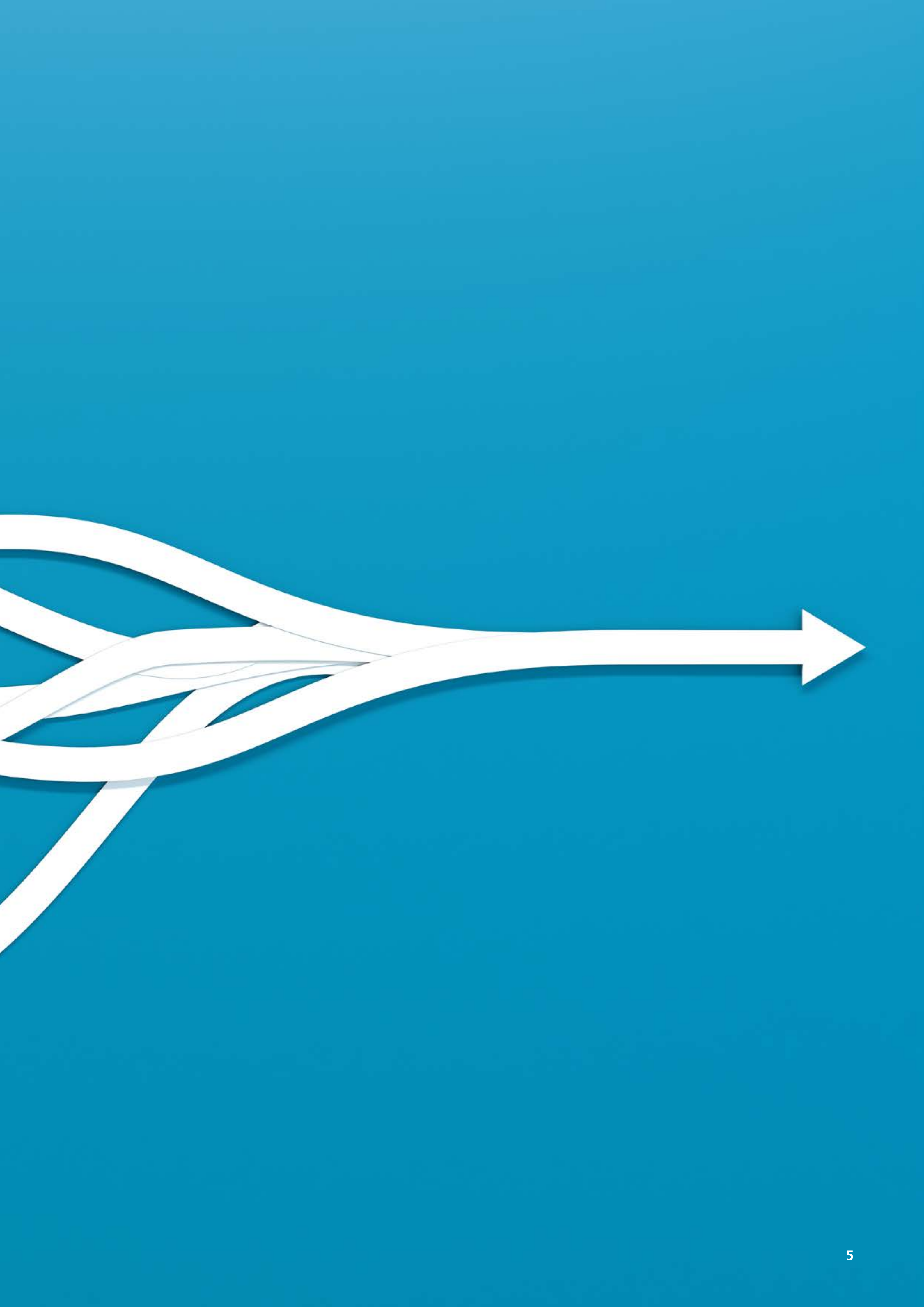
1 Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems (IEG)
2 Fraunhofer Institute for Environmental, Safety, and Energy Technology (UMSICHT)
3 Fraunhofer for Building Physics (IBP)
4 Helmholtz Centre Potsdam German Research Centre for Geosciences (GFZ)
5 Karlsruhe Institute of Technology (KIT)
6 Helmholtz Centre for Environmental Research (UFZ)

Table of Contents



Roadmap with five recommendations for the expansion of Deep Geothermal Energy in Germany

Summary and recommendation

Climate policy targets for the next two decades are high and an enormous demand for renewable energy sources is foreseeable. The decarbonisation of the heat sector requires a disruptive transformation process. In addition, to provide innovative technologies and capacity building for the industry, this process also involves the levels of governance, market regulation and incentives, finance and energy industry, and innovation and acceptance creation.

The **heat sector** accounts for 56 % of the national energy demand, underlining the energy and economic importance of the upcoming transformation process. Renewable energy accounts for only 15 % of heat, a share that has been stagnant for years. While hydrogen and bioenergy will primarily have to cover the high-temperature needs of energy-intensive basic industries in the future, solar and geothermal options mainly, are suitable for low-temperature uses below 200 °C. The advantages of geothermal energy lie in its base-load capacity and minimal space requirements, even in confined urban conditions with significant competition for use. In addition, the underground offers also a high heat storage potential.

The **strategy paper** discusses the possible contribution of geothermal energy to this transformation process. One focus is on **hydrothermal reservoirs**, i.e. thermal water-bearing rocks at depths between 400 m and 5,000 m. Deep wells tap geothermal waters with temperatures between 15 °C and 180 °C. These are available, regardless of the season and time of day and can be used in particular for **municipal heat supply, district heating**, **housing industry** and provision of **industrial process heat**. Hydrothermal systems, like other geothermal systems, have unlimited base load capacity. The technology is mature and has been deployed in several European cities for decades.

The market potential in Germany is well over **300 TWh of annual work** or **70 GW of installed capacity** (approx. **25 % of the total heat demand**). This applies first to the areas mentioned above with current or foreseeably available hydrothermal technologies for deep geothermal direct use alone or in combination with large-scale high-temperature heat pumps. Additionally, there is the potential for petrothermal energy, ample seasonal **underground heat storage** (> 500 TWh/yr) and surface geothermal energy used for heating and cooling buildings in the construction and housing sectors.

To build deep geothermal generation plants and connect them to municipal distribution infrastructures for heating, investments of approx. **2.0-2.5 billion euros per GW** of installed capacity from public and private households will be needed over the next decade. This will achieve **competitive heat production** costs of < 30 EUR/MWh.

For integrating geothermal energy into the energy mix, the **actors** from business, science, politics, and administration face complex implementation tasks. In this context, the municipalities have a prominent role to play. New support instruments for cities and municipalities must be created at various points. This strategy paper intends to provide all actors with the necessary information on the geothermal heat supply, the versatility of the heat market, the technological realisation of the heat transition with its challenges, and networked options for action.

> **"Geothermal energy is a relevant part of energy system integration in Germany and complements fluctuating energy sources, especially in the heating market."**

The strategy paper makes five recommendations for the expansion of geothermal energy:

1. **Policymakers** must formulate clear expansion targets; which legislators must underpin with regulations. **Accelerated approval procedures** with a concentration effect are just as much a part of this as the review of an amendment to laws (such as the BBergG, WHG, BauGB, UVPG, and GEG) and the **designation of preferential areas** in the regional development plans of the federal states and the municipal land use plans. At the same time, policymakers must make CO_2 avoidance costs the guiding tool of regulation, and the system of charges and levies for municipal and industrial producers and operators must be levelled and simplified.

2. In the short term, **effective instruments** are needed **to reduce the exploration risk**: economically, these are financial tools and a noticeable increase in the annual funding volume of the "Federal Funding for Efficient Heat Networks (BEW)" to well over 1 billion Euro. From a technical point of view, this includes geophysical investigations in conurbations as part of national geological surveys and an exploratory drilling programme to reduce exploration risk, as well as demonstration and pilot plants with keen scientific supervision.

3. Investments in 10-year **key technologies** for expansion to a large industrial scale by industry and accompanying government support programmes; e.g., in drilling and reservoir technologies (incl. engineered geothermal systems), borehole pumps, high-temperature heat pumps, development of large-scale heat storage, the expansion of trans-municipal heat grids and cross-sectoral system integration. In this context, comprehensive digitalisation must become the basis for analysing, planning, integrating, managing, and controlling complex energy systems.

4. Activating the **high potential for value creation and the labour market** of 5-10 people per MW of installed capacity along the value chain of research and development, component production, administration, plant construction and operation through measures to promote innovation and the economy. Education policy measures (curricula, further training, inter-company training centres, recruiting programmes) are needed to overcome low personnel capacities.

5. **Comprehensive public relations** work must be initiated and proactively supported politically. Promoting positive anticipation and acceptance in society requires a targeted strategy for interaction with citizens and stakeholders which creates participatory opportunities, especially at the municipal level.

1. Introduction

Background

For thousands of years, thermal springs have provided energy for thermal baths and heating buildings (Aachen, 64 AD). The first oil crisis in the 1970s led to an expansion and re-evaluation of geothermal energy for heating purposes and, for example, the development of geothermal-based heating networks in the suburbs of Paris. However, geothermal energy has so far played a significant role in national energy supply, mainly in regions of the globe with volcanic activity, i.e., where hot water is also found near the Earth's surface. Hence, the world's largest geothermally powered heating network covers 99 % of the demand of Iceland's capital Reykjavík. In Germany, geothermal heating centres were built in the 1980s, especially in the GDR, for example, in Neubrandenburg or Waren, where the thermal energy of the reservoir water was used in heating networks. In the Upper Rhine Graben, several boreholes were drilled simultaneously; among these, the plant in Riehen, Switzerland, continues to contribute to the supply of a heating network in Baden-Württemberg today.

Electricity has been generated from geothermal energy since 1913 when the first power plant was commissioned in Larderello in Italy. Germany's first electricity generation power plant was built in Neustadt-Glewe in 2003. Since then, around 16 GW_{el}. installed capacity has been added worldwide, primarily in areas with volcanic activity, such as California, Indonesia and New Zealand.

The German Bundestag had already recommended a range of measures to expand geothermal energy in 2004, proclaiming, among other things, the 1 GW target for electricity generation within a decade[1]. With the introduction of the Renewable Energy Sources Act (EEG) and guaranteed compensation for electricity fed into the grid, initial interest in geothermal energy in some parts of Germany was generated, especially in Upper Bavaria but also along the Upper Rhine (initially in the French Alsace, later also in Baden-Württemberg, Rhineland-Palatinate and finally in Southern Hesse. Thermal springs are also used for local heating projects in other areas such as North Rhine-Westphalia, Mecklenburg, Hamburg and Lower Saxony. Overall, however, geothermal energy still falls far short of its potential on a national level, especially in the heating sector.

1 Deutscher Bundestag (29.03.2004): (Drucksache 15/2729).

Geothermal energy's contribution to the heat transition

Geothermal energy's contribution to the heat transition. The goal of decarbonising the heating market in Germany can only be achieved by switching to renewable energy sources. If there is a rigorous switch from coal and natural gas to the largely CO_2-free solar, bio or geothermal sources, today's CO_2 emissions will fall below 10 % of today's value[2]. The Dutch Geothermal Energy Masterplan[3] (2018) outlines an exemplary path toward decarbonising a natural gas-based energy economy. Geothermal energy has a unique role in urban regions, as this energy source does not require large amounts of land (such as wind or solar parks) or increased transport (such as biomass). The potential in Germany is of considerable size and opens up the following expansion targets: over 300 TWh/yr, i.e., a quarter of the German heat demand, could theoretically be covered by deep geothermal energy systems combined with high-temperature storage and the use of mining water[4]. Up to here we spoke about heat recovery from water bearing horizons, so called hydrothermal systems. If the potential of petrothermal systems, i.e. systems where additional water is required to extract the heat, is added in the long term, the contribution is significantly higher. Added to this are the near-surface geothermal systems for heating and cooling in new buildings so that an expansion target of about 500 TWh per year from geothermal energy seems realistic.

Geothermal technologies

Utilising hydrogeothermal resources requires at least one production well and one injection well on-site, connected via a thermal water-bearing rock layer. The energy from the extracted water is transferred above ground (i.e. at the earth's surface) to the relevant consumer, and the cooled water is returned to the reservoir via the injection well. A thermal water circuit of this kind can use the natural temperature conditions in the underground or the increased storage temperatures due to artificially injected thermal energy (see below). Compared to closed systems, i.e., borehole heat

2 IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011.

3 Master Plan Geothermal Energy in the Netherlands – A broad foundation for sustainable heat supply (05/2018).

4 RED II-Bericht der BRD an die EU-Kommission 2018/2001 zum Potenzial der Nutzung von Energie aus erneuerbaren Quellen. 2020.

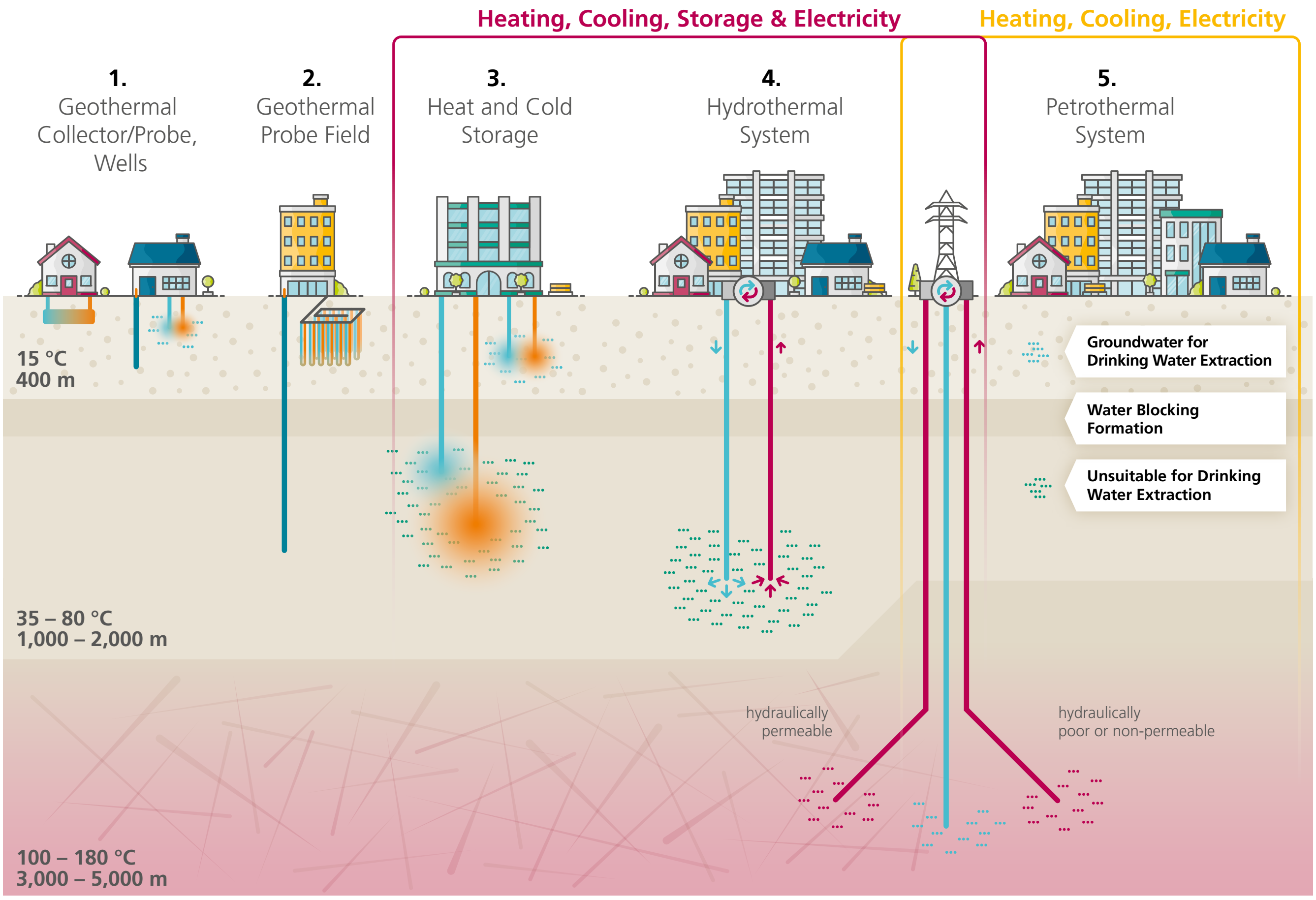


Figure 1: Geothermal systems for storing and providing heat as well as cooling and electricity (© GFZ). Near-surface technologies (left) are already marketable. The red border represents the scope of the hydrothermal systems dealt with in the strategy paper; the yellow border shows petrothermal systems.

exchangers, which transfer heat purely by conduction, open systems allow a significantly higher heat output per borehole due to the circulation of the reservoir water. Figure 1 shows simplified closed (examples 1 and 2) and open systems (examples 3-5).

Hydrothermal geothermal energy

Hydrothermal geothermal energy is based on the use of hot thermal waters that move along natural pore, fissure and fracture systems, i.e., through cavities in the subsurface. These are tapped utilising deep wells, analogous to the drinking water industry. The spa industry has been using thermal waters for centuries in Central Europe and worldwide. In the past century, wells have also been increasingly used for energy purposes. These wells usually penetrate deeper to achieve higher water temperatures for heating networks. Hydrothermal systems are state of the art and are already successfully used commercially in Munich, Paris and many other locations worldwide.

Petrothermal systems

Petrothermal systems, on the other hand, are attached to hydraulically conductive water pathway structures in the almost dry subsurface. These systems use the heat available at great depths (e.g., 200 °C at a depth of 5 km) and bring in water as a heat-conducting medium from the surface. Technologies that increase the permeability of these systems and open them up environmentally friendly are available for this process[5] (e.g., drilling technologies, hydraulic stimulation or acid treatment). Research and development recently provided further ecologically friendly technologies in the context of engineering measures. For example, some of the deposits in the Upper Rhine Graben at the transition area from hydrothermal to petrothermal systems are now in economic exploitation[6,7]. One can assume that the geological conditions in many regions of Germany would permit petrothermal systems.

5 Huenges E. (2014) in Geothermie-Vorhaben Tiefe Geothermie: Recht, Technik und Finanzierung Jörg Böttcher (Hrg.), 151-164.
6 Bracke, R. (2014): Handbuch Tiefe Geothermie 245-272.
7 Held, S. et al.: E Geothermics 51, 270-280

Underground storage

The urban underground offers the possibility of storing heat and cold, which – considering the increasing use of fluctuating energy sources – stabilises the energy supply seasonally[8]. The principle is to store surplus heat from summer (e.g., from solar thermal energy or waste heat) in an aquifer, a water-bearing layer in the geological subsurface, and to use it as heating in winter. Flooded mine tunnels or gravel-filled basins can also serve as storage facilities. So far, the feasibility of such storage facilities has been demonstrated in a few projects in Germany. In neighbouring countries, e.g., the Netherlands, aquifer storage for cooling and heating buildings is routinely used in over 2000 projects, mostly at shallow depths[9].

Across Germany, the deeper subsurface offers excellent potential for high-temperature storage of large amounts of heat in many urban areas. This could cover a large part of the local heat demand and almost the entire demand for building cooling, which is expected to increase due to climate change. The integration of seasonal heat storage for the heat supply of urban districts is also becoming increasingly important. Geothermal heat sources and seasonal thermal storage systems serve the grid. They can contribute significantly to a reliable heat supply in the future and can be combined with other energy sources. Where aquifer storage systems cannot be used, geothermal probe storage systems are an economical and widely applicable alternative[10,11,12]. In this case, seasonal or industrial surplus heat is fed into deep geothermal probe fields and withdrawn again in reverse operation during periods of high demand. Such demonstration systems are already in operation.

Transformation process

Geothermal research is developing new ways to explore and use the subsurface in urban areas through a multidisciplinary approach[13]. The partial transition of the heat supply in the Munich metropolitan area to geothermal energy is an exemplary demonstration of the path towards a transformation process broadly supported by society. The extraction of geothermal energy is the safest geological energy source compared to conventional resources (natural gas, oil, coal, and nuclear fuels). Nevertheless, some concerns to the use of the subsurface exist in relation to seismic tremors and safe drinking water production. Here, the coupling of pilot projects and research infrastructures (e.g., GeoLaB, Reallabor Weisweiler) contribute in making the discussion more objective and minimising concerns. Sociological studies should also accompany the social transformation process to provide the actors with a sound basis for dialogue and citizen participation.

Compensating for market failures

Germany should significantly accelerate the expansion of geothermal energy as a substitute for fossil fuels to rapidly reduce CO_2 in the heat supply. In Germany, about 440,000 plants provide 4,400 MW of installed heat capacity from near-surface sources below 400 m depth[14]. Nationwide, 42 plants offer 359 MW of installed thermal capacity and 45 MW of electrical capacity[15] (2020). In contrast, no comprehensive market has been developed for profound geothermal energy, despite its great potential to compete with fossil fuels such as coal and natural gas. The framework conditions for expanding capacities must be significantly improved through various measures to achieve the political target of generating 50 % of municipal heat from climate-neutral sources by 2030[16].

8 Kranz, S., et al. (2015): Urban Design, 1, 1, 19-20.
9 Fleuchaus, P. et al. (2018): WRenew Sustain. Energy Rev. 94, 861–876.
10 Sass, I. et al. (2012): Tagungsband Der Geothermiekongress 2012. Karlsruhe, Germany.
11 Bär, K., et al. (2015): Energy Procedia, 76, 351-360.
12 Welsch, B. et al. (2018): Applied Energy 216, 73-90.

13 Huenges 2010 Geothermal Energy Systems, Wiley, 1-486.
14 BAFA, BVG, BWP / BDH-Absatzstatistik Wärmepumpen
15 Zeitenreihe EE des Statistischen Bundesamtes, Geotis, BVG
16 Koalitionsvertrag 2021-2025 zwischen SPD, Bündnis 90/Die Grünen und FDP

2. Geothermal Sources

Due to increasing temperatures with depth, the possibility of using geothermal systems to exploit the heat potential generally arises. Essentially, two prerequisites are necessary for the energetic use of geothermal resources: firstly, the thermal water temperature alone or in combination with heat pumps must be high enough for the foreseen use, and secondly, the hydraulic permeability of the rock must be high enough to allow the hot water to reach the surface in large quantities or at suitable flow rates.

Suitable geological formations for geothermal use in Germany can be found, for example, in sedimentary rocks in southern Germany, along the Upper Rhine Graben between Basel and Frankfurt a.M. and throughout western and northern Germany between the Netherlands and Poland[17]. In the heat-intensive Rhine-Ruhr region alone, the theoretically exploitable geothermal potential for hydrothermal systems is 20 times higher than the current heat demand[18]. However, not all regions of Germany are equally appropriate for the use of deep geothermal energy. Many potential formations are still insufficiently explored and not sufficiently characterised concerning geothermal production. Energy industry and politicians have shown insufficient interest in this field in the past, and geological services of the federal states have lacked the resources to fulfil the exploration tasks. Germany is consequently geothermally under-explored and it must be stated here that an excellent geoscientific database is essential for engineering planning.

Regions[19] known to have existing deep geothermal use in Germany and their geological formations[20] are briefly described below:

South German Molasse Basin (SMB): The region in the foothills of the Alps that has absorbed the weathering debris of the rising mountains is called the "Molasse Basin"[21]. The SMB extends from Switzerland through Baden-Württemberg

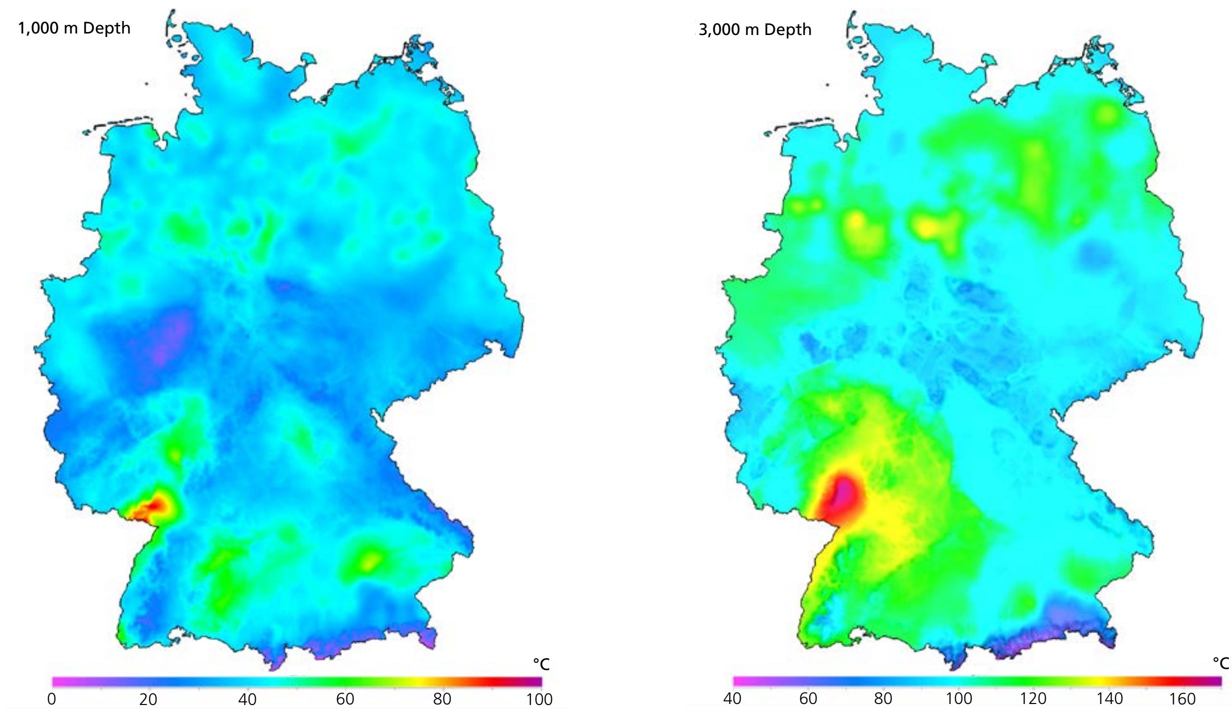


Figure 2: Temperature in Germany at 1 and 3 km depth based on drilling data (© Agemar, LIAG)

17 Geothermischen Informationssystem (GeotIS): https://www.leibniz-liag.de/forschung/methoden/informationssysteme/geotis.html
18 Bracke, R. et al. (2016): Geothermische Energie, Heft 84, 2016/2, 34-35.
19 Umweltbundesamt (2020): … tiefengeothermischer Ressourcen Abschlussbericht (31/2020).
20 Stober I. und Huenges E. (2013): Technologien und Systeme, in VBI Leitfaden Tiefe Geothermie, 8-12.
21 Keim et al (2020) Tiefengeothermie in Bayern – Forschungsprojekt Geothermie-Allianz Bayern (mediaTUM).

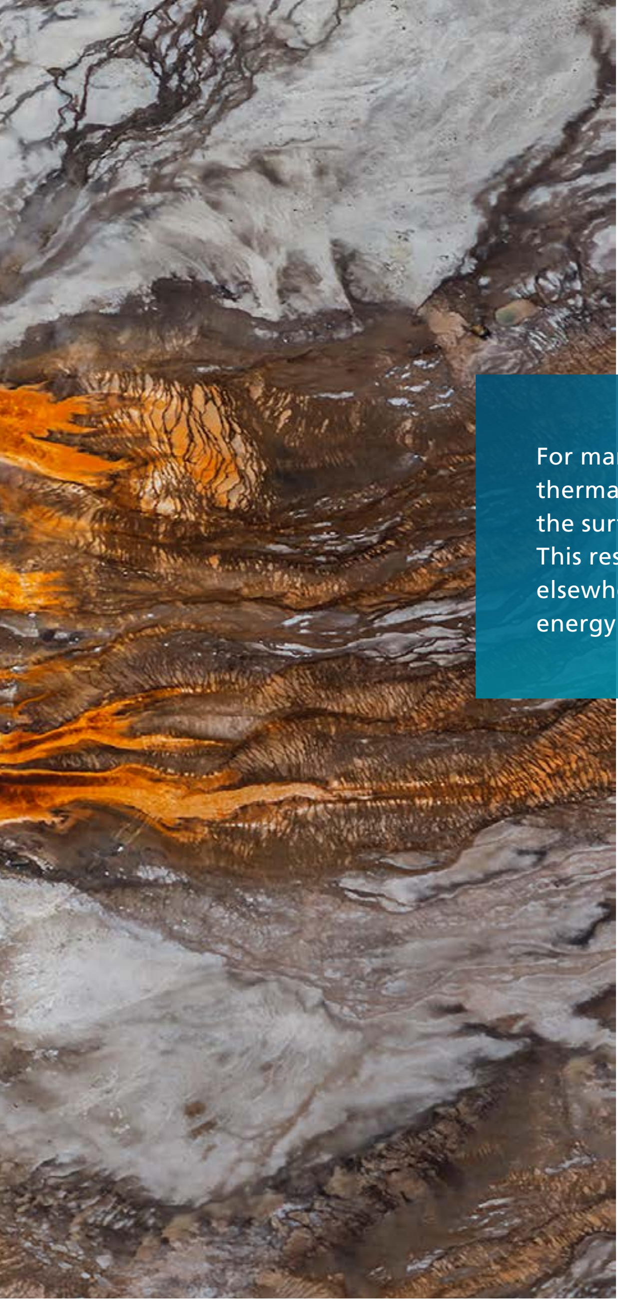
to Bavaria and Austria. The basin base is formed by gneisses and granites, which are overlain by sedimentary rocks with a maximum thickness of 8 to 10 km. The Jurassic carbonates, in particular, are used for geothermal energy, as these rocks have an exceptionally high yield due to karstification (partial rock dissolution). Temperatures between 100 °C and 155 °C and high permeabilities are possible and have been achieved south of Munich and in the Lake Chiemsee area with flow rates of over 300 m^3/h in some cases[22]. Towards the west, the hydraulic properties become less favourable.

Upper Rhine Graben (ORG): The Upper Rhine Graben stretches along the Rhine between the Swiss Jura in the south and the Taunus in the north. The six plants currently operating commercially produce hot thermal water mainly from the overlying sedimentary rocks and the transition horizons into the basement from 130 °C to 180 °C and have the potential to supply raw materials (e.g., lithium). At comparable depths, the Upper Rhine Graben has the highest subsurface temperatures measured so far in Germany, e.g., over 170 °C at a depth of 3 km below the Karlsruhe Institute of Technology[23]. In the ORG, fissured areas of the basement also have excellent reservoir properties in some cases[24]. High storage potential of 10 TWh/yr was determined for the former hydrocarbon reservoirs of the Upper Rhine Graben[25].

North German Basin (NDB): The North German Basin extends from South Lower Saxony to below the North Sea and the Baltic Sea. The basin filling consists of a rock sequence up to 5,000 m thick, with volcanic rocks forming

22 https://www.geothermie.de/geothermie/geothermie-in-zahlen.html

23 Baillieux, P. et al. (2013): International Geology Review 55 (14), 1744–1762.
24 Bächler, D. et al. (2003): Physics and Chemistry of the Earth, Parts A/B/C 28 (9), 431-441.
25 Stricker, K. et al. (2020): Energies 13 (24), S. 6510. DOI: 10.3390/en13246510.



For many centuries, people have been using thermal waters where they naturally come to the surface, for example in the spa industry. This resource can also be found in the depths elsewhere and made usable for a sustainable energy supply by means of deep wells.

the base on which different sedimentary rocks are deposited. At depths of 4,000 to 5,000 m, temperatures here range between 130 °C and 160 °C. Conglomerates and sandstones, occurring at different depths, are particularly satisfactory for geothermal use. The thermal waters in some of these sedimentary layers have a very high content of mineral raw materials (e.g., lithium with > 200 mg/litre, as proven in fluids of the Rotliegend).

Rhine-Ruhr Region (RRR)[26]: In the RRR, the hydrothermal reservoirs primarily consist of karstified limestone and dolomite, fissured sandstone (East Westphalia) and volcanic rocks (Eifel) in the basement. The mass and reef limestones contain essential, and in part compelling, hydrothermal reservoirs at depths of 2 to 5 km with thermal waters at temperatures of 70 °C to 170 °C, distributed over a wide area from Westphalia and the Sauerland through the Rhineland to well beyond the western German border, including several uses in the Netherlands and Belgium. In addition, mine water has great thermal utilisation potential from hard coal and ore mining in North Rhine-Westphalia[27], Saarland and Saxony.

Basement: The older rocks beneath the sedimentary basins are called basement. The base of the North German Basin is formed by dense sedimentary rocks that lie at depths greater than 5,000 m. Between the North German Basin and the South German Depression lie the low mountain ranges built of impermeable gneisses, granites, and very old sedimentary rocks. The basement in deeper areas of these regions, which are suitable for hydrothermal systems, plus other regions, forms about 95 % of the geothermal energy potential.

26 Bracke, R. et al. (2016): Geothermische Energie, Heft 84, 34-35.

27 Bracke, R. et al. (2018): Potenzialstudie Warmes Grubenwasser. LANUV-NRW, Fachbericht 90.

3. Heating Requirements

The German metropolitan regions with their industrial cores, i.e., the country's 80 major cities, account for the largest share of the final energy share of approx. 2,500 TWh/yr. Of this – besides the city-states of Berlin, Hamburg and Bremen – 38 % is in NRW, 11 % in Baden-Württemberg, 10 % each in Bavaria and Lower Saxony and 6 % in Hessen.

3.1 Regional and Sectoral Demand

Heating sector

Heating accounts for most of the final energy demand with a share of 56 % or approx. 1,400 TWh/yr (2019). Heat consumption can be broken down into space heating (658 TWh/yr), hot water (130 TWh/yr), process heat (541 TWh/yr) and air conditioning/process cooling (63 TWh/yr). The most important heat sources are mineral oil and natural gas (Fig. 3). Thus, with 67 %, there is a strong dependence on fossil fuels in final energy consumption. For district heating, the share of fossil heat supply lies at 80 %[28].

The majority of heat is needed in densely populated regions. This applies to space heating / private households as well as to trade, commerce and services, especially in large areas of North Rhine-Westphalia, as well as the metropolitan areas of Hanover, Braunschweig, Göttingen, Bremen, Hamburg, Kiel, Berlin, Hesse / Rhine-Main, Baden-Württemberg / Rhine-Neckar, Munich-Augsburg-Nuremberg and parts of Saxony (Fig. 4). 60 % of the overall heating demand requires temperatures below 180 °C and thus lies within the geothermal temperature window. This includes the heating demand of private households, commerce, trade, services and industrial low-temperature process heat. Municipal grid-connected heating systems also operate in this temperature range (90-130 °C). Of the 290,000 TJ or 80.7 TWh of heat fed into German interconnected grids annually, the district heating grids of the Rhine-Ruhr region alone consume approx. 15 TWh/yr. In food production and industry, there is great demand for process heat in the temperature range between 50 °C and 200 °C. This demand can also be addressed by deep geothermal energy or by combining deep geothermal energy with high-temperature heat pumps, for example. Process heat is required at even higher temperatures, especially in energy-intensive industries such as steel, cement and glass production, and the chemical industry.

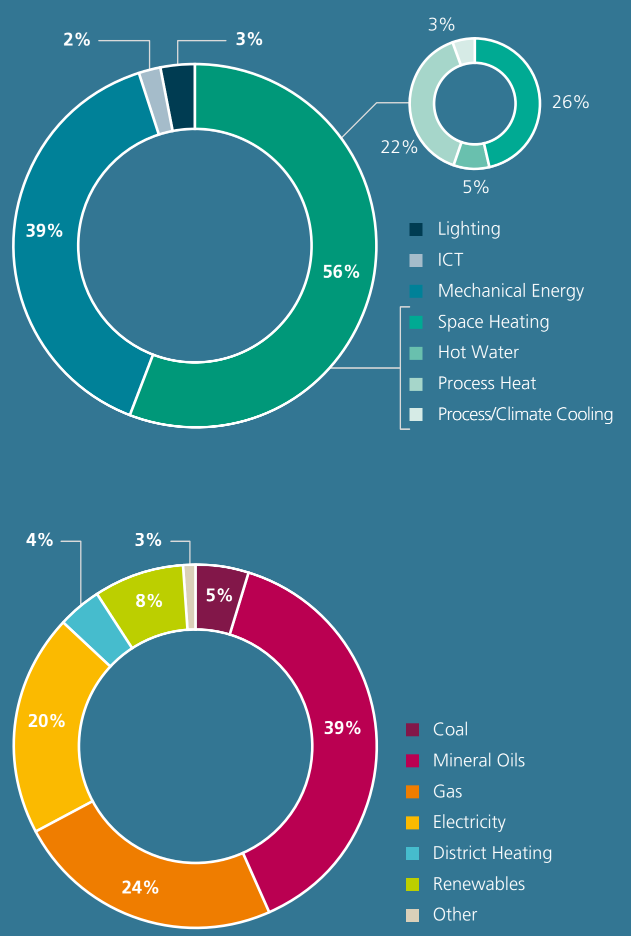


Figure 3:
Final energy consumption (2,514 TWh) in 2019 by application (top) and by energy source (bottom)[29].

28 BMWi, 2020.

29 BMWi, 2019.

The phasing out of coal-fired power generation and the associated discontinuation of heat extraction directly impact the district heating supply. About 13.3 GW of secured heat bottleneck capacity is directly affected. These plants feed around 40 TWh/yr into public district heating networks, which alternative heat sources must replace. In this context, it is essential to consider the system integration of new heat sources, grids, storage facilities and the coupling of heat supply with the electricity, cooling and, if necessary, transport sectors to advance the transformation process of the energy transition.

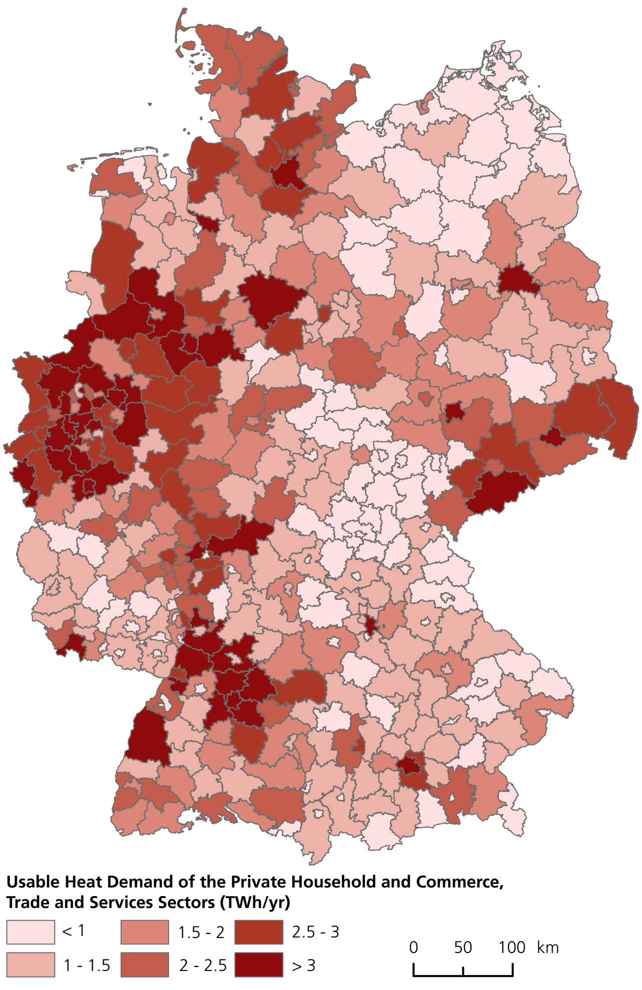


Figure 4:
Regional distribution of useful heat demand in Germany (2014) for private households (PHH) and trade, commerce, services; excluding industrial process heat (© Eikmeier, Fraunhofer IFAM)[30].

30 Eikmeier, B. (2014): Potentiale für Nah- und Fernwärme auf KWK-Basis.-Fraunhofer IFAM.

Based on the Federal Climate Protection Act (KSG 2021), the **building sector**, which is particularly heat-intensive, has the task of gradually reducing its CO_2 emissions by 43 % from 2020 to 2030[31]. The required temperature is between 30 °C and 70 °C and can usually be easily covered by geothermal systems. This means that the conversion of energy supply to existing properties and the new construction of neighbourhoods in the housing industry play a vital role in the heat transition.

3.2 Heat Distribution

Low-Temperature District Heating

At temperatures between 15 °C and 60 °C, low-temperature district heating (LTDH) – also known as cold grids – can manage the heat supply much more efficiently than conventional heat grids and facilitate the integration of renewable energy sources. Low-temperature heat grids allow considerably more economically feasible local and district heating pipeline infrastructures to be built compared to networks with higher operating temperatures. To date, low-temperature heat grids have not been sufficiently used in Germany. They do, however, represent an essential option for the housing industry.

LowEx Grids

An extension of the low-temperature district heating networks is the development of low-exergy heating grids, so-called LowEx grids. These allow users to be both consumers and producers of heat and cold (prosumers). The grids can supply different users with their demand-based temperature. Still, they can integrate other decentralised heat generators, such as solar thermal, geothermal, waste, or process heat[32].

Conventional Heating Networks

The majority of existing heating networks in cities operate at higher temperature levels. Large-scale conversion to LowEx or low-temperature heat networks is improbable due to the diverse municipal consumer structure[33]. Conventional local and district heating networks heat at temperatures between 70 °C to 130 °C with a thermal output of 1 MW to

31 Erstes Gesetz zur Änderung des Klimaschutzgesetzes vom 18.08.2021 (BGBl. I S. 3905).
32 Stănişteanu 2017.
33 Nussbaumer et al. 2018: Biedermann und Kolb 2014.

1 GW. At present, the transformation to the fourth district heating generation is taking place in some cases[34]. This involves lowering the supply temperature to below 60 °C so that low-temperature heat sources, especially renewable energies, can be integrated. However, most of the district heating networks operated in Germany do not have these technical boundary conditions and are supplied by more than 80 % of fossil fuels[35]. Since a significant reduction in the operating temperatures of these networks is not feasible in most cities due to supply obligations and evolved and heterogeneous consumer structures, the challenge is to convert the source from centralised fossil fuels to centralised geothermal heating plants or many decentralised RE generators and change load management.

Cities

Today, district heating networks are operated in ~ 95 % of German cities (80 cities with more than 100,000 inhabitants) to provide building heat (approx. 50 %) and industrial process heat. All large German cities are expected to use district heating by 2030 and expand this from 88 TWh/yr to 114 TWh/yr annual work by 2050 (Fig. 5). In medium-sized cities (approx. 620 towns with 20,000-100,000 inhabitants), an increase from 20 TWh/yr to 42 TWh/yr is expected. Furthermore, an increase in the share of medium-sized towns with district heating supply from 50 % to 80 % by 2050 is forecast. A similar development is predicted in approximately 1,390 small towns (< 20,000 inhabitants), where the share of municipalities with district heating is expected to increase to 60 %.

Industry

The share of industrial processes in district heating demand is 50 TWh/yr (44 %). This demand is expected to increase considerably less than residential heating demand, as many companies operate and modernise their generation plants for process steam, heat or electricity. The efficiency improvements in the industrial sector are more significant than in the building sector. However, the generation of process steam with almost preheating input from geothermal energy and the feeding of industrial waste heat into municipal heating systems should gain importance in the future if an infrastructural connection of the producers is made.

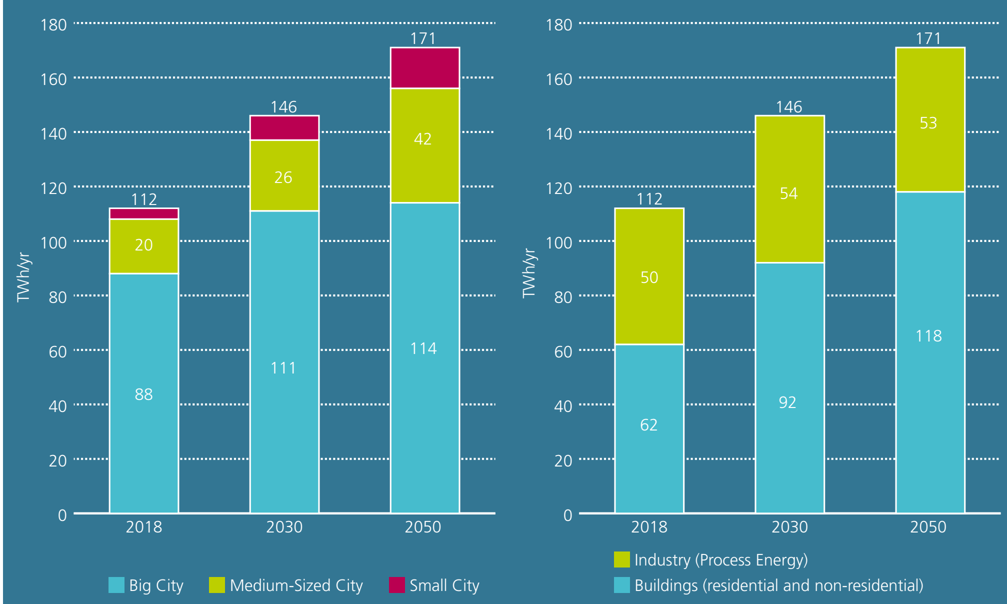


Figure 5: Future district heating demand in large, medium and small cities forecast for 2018, 2030 and 2050[36].

34 Huenges E., et al. (2014): FVEE-Jahrestagung 2014, 96-101.
35 BMWi, 2020
36 Thamling et al. (2020): Gutachten Perspektive der Fernwärme Maßnahmenprogramm 2030.

Rural Areas

About a quarter of the German population lives in village structures. As a rule, these areas do not have a grid-connected heat supply. In most cases, the heat supply is decentralised and organised based on oil and gas. For this reason, the politically targeted expansion of "citizen energy" is significant, especially in smaller communities or districts. Similar to the operation models of wind and solar parks in the electricity sector, the grid-connected heat supply through, for example, cooperatively operated geothermal plants could contribute significantly to decarbonisation in rural areas.

3.3 Heat Demand in Industry and Food Production

IThe German industry's most significant combined heating and cooling demand of 604 TWh/yr (2019) is in metal production, basic chemicals, paper production, processing of stones and earth, and food. Due to the individual industrial processes, the required thermal energy must be provided in specific temperature windows (Fig. 6). The energy-intensive basic materials industry requires most of the heat at temperatures far above 500 °C. This cannot be addressed by geothermal sources.

Locally, geothermal temperatures of up to 140 °C can be provided throughout Germany. If this is insufficient, it will be possible to increase the temperature in the future, e.g., in combination with large-scale high-temperature heat pumps or other processes. In the future, process heat and process steam generation up to the temperature range of 200–500 °C (Fig. 6) are conceivable in such process combinations. In addition, all sectors have a primary demand for space heating, hot water and low-temperature process heat, which can be covered geothermally anyway. Overall, the technical geothermal potential can roughly cover 500 to 600 PJ (130 to 150 TWh) or up to a quarter of the useful industrial heat demand.

Possible target sectors for the conversion of process heat and process steam provision to geothermal sources are textile and paper production, wood processing and construction, chemical, metal processing and other low-temperature intensive industries, as well as (greenhouse) agriculture and the production and processing of food and beverages. This selection already includes the expectations for the future development of final energy consumption.

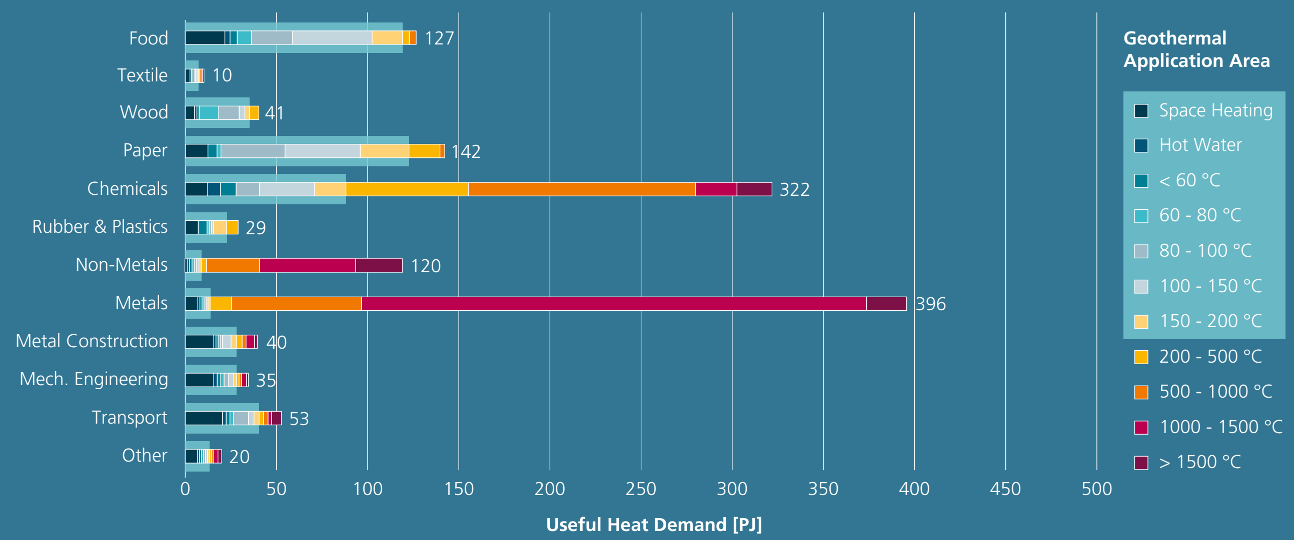


Figure 6: Sector-specific breakdown of useful heat demand by application and temperature level (3.6 PJ = 1 TWh)[37]. Geothermal sources in direct use or in combination with large-scale high-temperature heat pumps can cover the demand for useful heat up to 150 °C and in the medium term (up to 2030) up to 200 °C.

37 Wolf, S. (2016): Potenziale und Instrumente zur Potenzialerschließung Dissertation Uni Stuttgart.

Industry in Germany has a base demand for low-temperature process heat in the geothermal window of up to 200 °C. Suitable thermodynamic converters combined with geothermal reservoirs could cover about a quarter of the industrial useful heat demand between 500 and 600 PJ.

The requirements of the individual sectors are as follows:

Construction industry, pulp and paper production, wood processing

The production of cement-based raw materials for the **construction industry** is highly energy-intensive. Besides drying processes, geothermal energy sources cannot meet this demand in the foreseeable future. However, integrating cellulose and wood-based building materials could reduce greenhouse gas emissions. There would be increased potential for geothermal energy in their manufacturing processes.

The **paper industry** is one of the five most energy-intensive sectors in Germany[38]. Regardless of the type of paper, drying to a residual moisture content of about 5 % is the most energy-intensive step in paper production. Energy is also required for water management, wastewater treatment, and residue and sludge treatment. Initial projects in the paper industry in Hagen (NRW) plan to convert these processes to geothermal energy.

In the **wood processing industry**, the drying process currently accounts for up to half of the energy demand. In addition, there is the hall heating of varnishing plants and heat demand for the varnishing process and the pressing of wood. The latter requires heat at temperatures between 120 and 270 °C.

Chemical and metal processing

The **chemical and metal processing industries** are based on high-temperature processes but also involve important production steps at temperatures up to 150 °C. Granulate drying in the plastics industry and other recurring tasks across industries such as boiling, evaporation and distillation are suitable for using heat from geothermal sources at low temperatures up to 150 °C.

In the metalworking industry, many processes take place at temperatures significantly below 150 °C: Pickling, degreasing, galvanising, phosphating, curing, washing and drying, thus providing a wide range of application options for geothermal heat supply in the base load range.

Food production and processing

The industrial production of flowers, fruit and vegetables in greenhouses requires large amounts of heat for heating at a relatively low temperature of 20 to 40 °C. In this segment, a very successful industry has developed over the past decade, especially in the Netherlands, converting its heat supply from fossil sources to geothermal.

The **food industry** also has a great demand for heat. Dairy processing, brewing, meat processing, dough production and bakeries consume half of the energy of all food companies. In food production and processing, heat in the geothermal temperature range is required in many different production steps. Examples include the tasks of washing, drying, heating, cooling, pasteurising, sterilising, preserving, distilling and sanitation.

38 www.umweltbundesamt.de

4. Solutions to cover the Heat Demand

4.1 Strategies

Almost all scientific models on the future energy systems assume a substantial increase in the availability of electricity and forecast an increasing heat supply via heating networks with the given demand for auxiliary energy[39]. In the future, heating grids are expected to provide 50 % of the municipal supply. Base-load geothermal energy can ensure the stabilisation of the supply. This gives power-to-heat (PtX) solutions a high priority within Europe[40].

Here, seasonal underground storage plays a vital role in the sector-coupled energy supply with PtX. Further flexibility is provided by short-term storage and by the heat grid itself. The Heat Roadmap Europe[41] shows that, in particular, the expansion of heating grids and the use of renewable energies – especially geothermal energy – to cover municipal and industrial heating needs offer a sustainable solution for decarbonising the heating sector.

The strategic research programmes and infrastructures of the Fraunhofer-Gesellschaft and the Helmholtz Association address these topics and provide the basis for the transformation of the heating sector.

High process temperatures of > 200 °C in the industry will probably have to be met by technologies based on the combustion of green hydrogen or biomasses/gases. At the same time, the low-temperature or building sector does not generate any relevant hydrogen demand in the short and medium term[42]. Therefore, renewable energies for electricity and heat generation combined with heat pumps must serve the industrial and municipal low-temperature range of < 200 °C in the long term[43]. Not least, due to its base load capability, geothermal energy has a decisive role to play here.

4.2 Heating and Cooling Generators

Geothermal waters can either be used directly or – if the reservoir cannot supply the required temperature – brought to usable temperatures through thermodynamic converters. In the PtX sector, the most significant contribution to the provision of heat is attributed to heat pumps[44]. In combination with near-surface borehole heat exchangers (up to a maximum depth of 400 m), they represent state-of-the-art technology for heating and passive cooling of residential buildings[45]. Heat pumps can transfer heat from a low to a higher temperature with small amounts of high-quality drive energy, such as electricity. The electric current is used to compress a working fluid previously vaporised by environmental heat to transfer latent heat to the hotter circuit through condensation. In addition to heat pumps for heat supply, absorption and adsorption units based on geothermal heat of > 80 °C can provide cooling, which can be used for large-scale cooling purposes.

The use of heat pumps in the construction and the housing industry in Germany has so far been limited mainly to buildings and local heating networks with temperatures up to 80 °C. Heat pumps for this application are commercially available up to high nominal power ratings. Thus, they can generate space heating, hot water and partly process heat – see the temperature range in Fig. 6[46]. In the industrial sector, units up to 100 °C are standard, and prototypes already generate a temperature swing up to 140 °C (Fig. 7). Industrial waste heat or heat from the air or underground is used as a heat source. Near-surface geothermal systems require 1 kWh of electricity for a heat pump to provide about 4 kWh of heat (efficiency COP = 4). Due to higher temperatures, systems from deep geothermal sources offer up to 20 to 50 kWh of heat with 1 kWh of electricity, depending on the location.

39 Pfluger, B. et. al.: https://www.bmwi.de/Redaktion/DE/Artikel/Energie/langfrist-und-klimaszenarien.html
40 EC, 2021a.: "Fit für 55": auf dem Weg zur Klimaneutralität – Umsetzung des EU-Klimaziels für 2030. COM/2021/550 EU Commission.
41 Heat Roadmap Europe: https://heatroadmap.eu
42 Fraunhofer (10/2019): Eine Wasserstoff-Roadmap für Deutschland.
43 In4Climate.NRW (2021): Industriewärme Klimaneutral: Strategien und Voraussetzungen für die Transformation.

44 Paardekooper et al. 2018.
45 Born, H. et al. (2017): Analyse des deutschen Wärmepumpenmarktes – Bestandsaufnahme und Trends 2017.
46 Arpagaus et al. 2018.

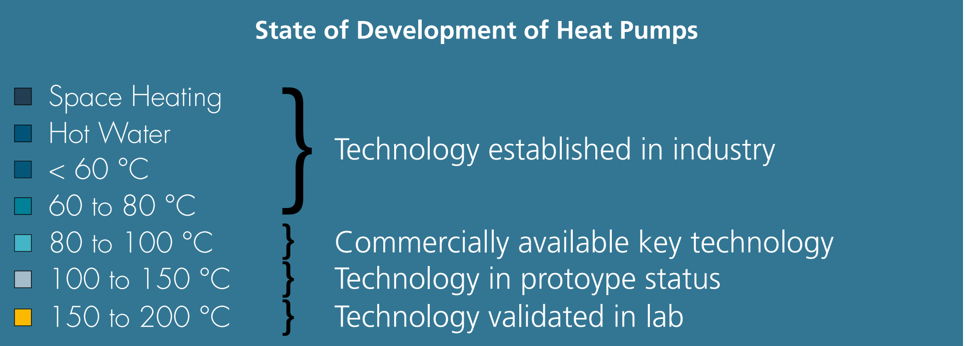


Figure 7: Development status of heat pumps for different temperature levels[47].

On the development side, high-temperature heat pumps up to 200 °C and nominal power ratings of up to 50 MW must be made commercially available in the next few years. This would make it possible to cover a large part of the heat spectrum of municipalities, the energy sector and industry based on geothermal heat. At process temperatures of 200 to 300 °C and similar working machines' quality, similar system efficiency advantages are achieved as with conventional heat pumps. This can, however, only be achieved through the further development of heat pumps and the use of new alternative circulation media.

4.3 Cross-sectoral Aspects

For power-to-heat technologies – i.e., heat pumps, direct current heating, storage heating, electrode boilers, electric industrial furnaces and large-scale continuous flow heaters (BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. 2020) – it is imperative to minimise the use of auxiliary electrical energy to provide heat and simultaneously integrate as much environmental heat into the system as possible. Electricity from renewable energy sources can make a sustainable contribution to the heat transition by linking electricity for driving thermodynamic converters for heat or cold generation and geothermal heat. Furthermore, their optimised system integration, including short-term and long-term thermal storage integration, can effectively contribute to electricity grid stability.

4.4 Expansion of the Network Infrastructure

The expansion of heating networks in connection with the development of waste heat and environmental heat potentials is deemed an essential component of heat supply decarbonisation[48]. According to the Climate Protection Programme 2030, renewable energies and waste heat are to be used more intensively in heating networks. In addition to geothermal heat generation, the necessary infrastructure for heat distribution still needs to be provided in many places or adapted to modern standards (decentralised feed-in, multi-directional load management) and future demand. The expansion of the grid infrastructure must be coordinated with the housing industry and oriented towards the demand for cooling and the possibility mentioned above of sector coupling.

4.5 Underground Heat Storage

To counteract temporal and spatial disparities in consumption and thermal energy production, short-term and seasonal storage options for heat and cold must be created on several size scales[49]. The combination of seasonal heat storage and combined heat and power (CHP) improves the economic efficiency of demand-responsive electricity provision in an energy system. By storing surplus heat during periods of low heat demand, CHP plants can be operated on a year-round power basis. The surplus heat stored in the warm season is used in the heating period when heat demand is high. The capacity of all district heating storage facilities (unpressurised, pressurised, 2-zone) in Germany is approx. 570,000 m^3 storage volume or 0.022 TWh capacity[50]. In addition to technical development and infrastructural integration, energy storage facilities will be established as a legally independent pillar of the energy system in the future.

Aquifers

In addition to the above-mentioned surface storage facilities, groundwater-conducting strata are a promising option for storing heat and cold in large industrial and municipal consumer structures. Natural underground storage is particularly

47 Arpagaus et al. [12], [14].
48 Paardekooper et al. 2018.
49 Blöcher, G. et al. (2019): System Erde, 9, 1, 6-13. https://doi.org/10.2312/GFZ.syserde.09.01.1.
50 Kühne, J. (2020): Wärmespeicher aus Sicht der Fernwärmebranche.- AGFW AK Langzeitwärmespeicher.

suitable for heat that accumulates in the summer season, both through the provision of industrial surplus heat from renewable energy sources and building cooling. Aquifer storage in ~300 m depth for heating and in ~50 m depth for cooling has been installed at the parliament buildings in Berlin in 2000[51].

Underground storage can be seen as a highly efficient system, which efficiency increases with the number of loading and recovery cycles over the years: While initially 70 % of the stored heat is returned to the energy supply system, after the 10th cycle, it is already over 80 %. An expansion of high-temperature aquifer storage (HT-ATES) at greater depths offers many advantages: it can be used in many locations, has no impact on drinking water reservoirs, and temperature level in the storage horizon can be adjusted to meet demand. Currently, several projects are in the implementation phase, including the DeepStor project at KIT-CN. Supposed it is possible to connect in terms of infrastructure and space, the use of depleted gas and oil reservoirs can be attractive due to the principally favourable state of porosity and permeability and the existing subsurface data stock. In addition, the storage in connection with near-surface geothermal probes (< 200 m) is already widely used for individual properties and neighbourhoods.

Modern (hammer) drilling methods make it economically feasible to drill geothermal wells to depths of over 2,000 metres. This makes it possible to build medium-depth borehole heat exchangers (BTES), which, in contrast to near-surface geothermal reservoirs, consist of a smaller number of deeper borehole heat exchangers. This reduces the space required at the surface, making this technology particularly attractive for use in densely built-up urban areas.

Mine thermal energy storage

On a large scale, flooded mines have a considerable storage volume and potential. In addition, due to their industrial history, these are usually located near the large consumers in the metropolises. Municipal mine water projects in the Netherlands, the Aachen coalfield, and the Ruhr region are already successfully operated in former mines. The TRUDI mine thermal energy storage facility in Bochum is currently being charged to up 60 °C using solar thermal energy and then fed into the existing district heating network in Bochum using high-temperature heat pumps as an example for the RRR.

51 Huenges, E. Thermische Untergrundspeicher in Energiesystemen: Optimierung der Einbindung der Aquiferspeicher in die Wärme- und Kälteversorgung der Parlamentsbauten im Berliner Spreebogen: Abschlussbericht; Berichtszeitraum 01.09.2005 – 31.10.2011. Potsdam: Helmholtz-Zentrum Potsdam GFZ Deutsches Geoforschungszentrum; 2011.

At the Zollverein Coal Mine World Heritage Site in Essen, a neighbourhood draws hot mine water from the former mining site for heating. Water-filled mines can also serve as large seasonal heat reservoirs underneath urban areas.

Assuming a residual void volume of only 10 % in the flooded mine infrastructures of hard coal mining and a ΔT of 50 K, a heat quantity of approx. 500 TWh/yr could be stored in German collieres.

4.6 Development of Regional Geothermal Resources

The regional distribution of potential hydrothermal reservoirs in the North German Basin (NDB), the Rhine-Ruhr Region (RRR), the Upper Rhine Graben (ORG) and the South German Molasse Basin (SMB) with elevated temperatures on the one hand, and the municipalities and districts with significant heat demands on the other, is largely congruent (Fig. 8). Thus, the hydrothermal potentials in metropolitan and urban areas with high useful heat and industrial process heat demands are particularly important.

So far, the technical supply potentials for electricity generation[52] and heat provision from hydrothermal geothermal

52 Geothermie-Allianz Bayern (2017): Potential der hydrothermalen Geothermie zur Stromerzeugung in Deutschland.

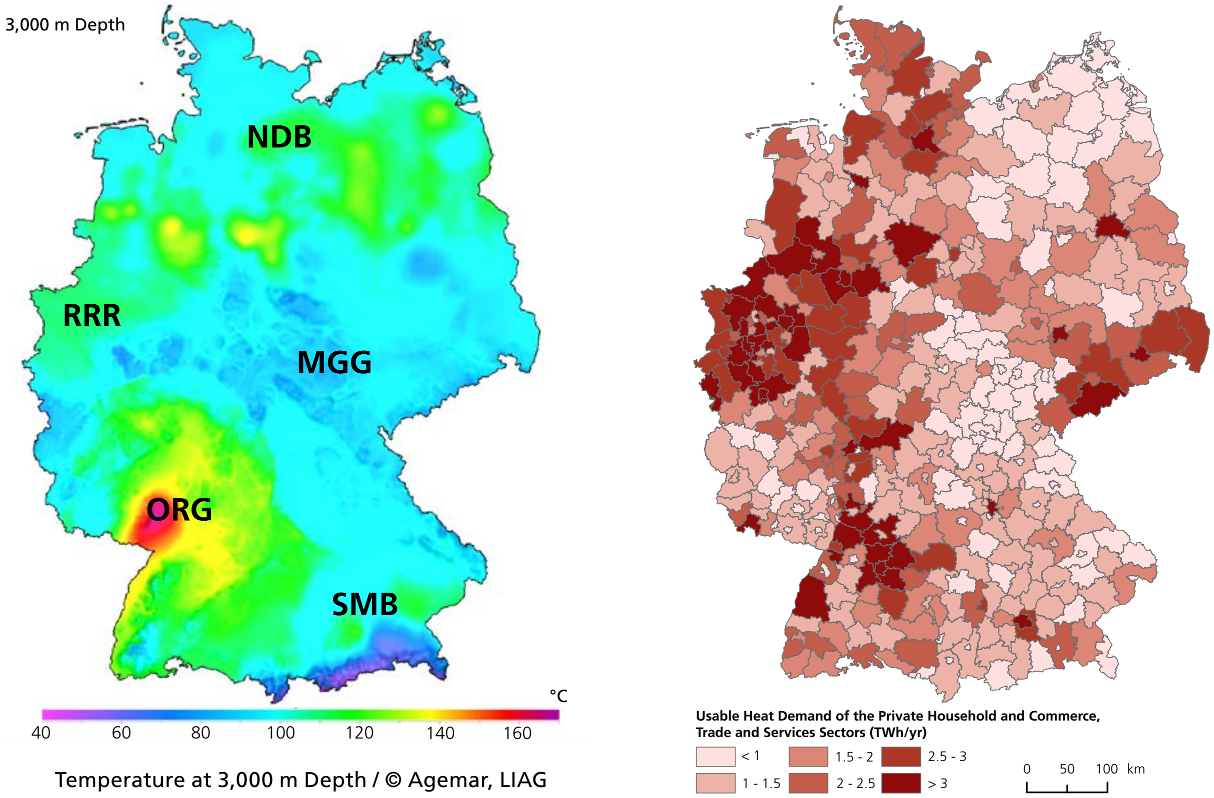


Figure 8: Comparison of geothermal supply with temperatures at a depth of 3,000 m (left: modified after Agemar / LIAG) and regional heat demand in Germany (right: Eikmeier / Fraunhofer IFAM). Left image: Temperatures [°C]; NDB = North German Basin, RRR = Rhine-Ruhr Region, ORG = Upper Rhine Graben, SMB = South German Molasse Basin, MGG = Central German Basement. Right image: Usable Heat Demand of the Private Household and Commerce, Trade and Services Sectors (TWh/yr)

energy for the regions NDB, RRR, ORG and SDM[53] have been determined. The Federal Environment Agency has had the potential to investigate four different scenarios in the NDB+ORG+SMB regions. The four scenarios each distinguish between two different reservoir temperatures (T1=65 °C / T2=35 °C) and qualities of exclusion areas of nature and landscape protection under the assumption of 2,500 annual total load hours per heating plant. The two extreme scenarios vary between 96 TWh/yr and 279 TWh/yr; 57 % of this is in the NDB, 8 % in the ORG and 35 % in the SMB[54]. However, these assumptions would have to be increased in terms of percentages for industrial process heat and hot water supply (8,600 h/yr each).

If the UBA scenarios are supplemented by the considerable potentials offered by the sedimentary rocks in western Germany / North Rhine-Westphalia, another approx. 92 TWh/yr is added in the Ruhr area. The extended RRR – i.e., including the Rhineland, Münsterland and East Westphalia – potentials of 120 to 150 TWh/yr do not seem unrealistic[55,56].

Thus, expansion targets between a conservative 220 TWh/yr and an ambitious 430 TWh/yr can be formulated for deep geothermal energy in the hydrothermal priority regions NDB, RRR, ORG and SDM. Conservatively, **Germany's total assumed technical potential is 300 TWh/yr** for hydrothermal reservoirs alone. Added to this are the petrothermal potentials in the basement (MGG), the considerable heat potentials from the mine waters of the mining industry and the large underground reservoirs. Deep geothermal energy could cover at least a quarter of Germany's heat demand.

53 Agemar et al (2014): Zeitschrift der Deutschen Gesellschaft für Geowissenschaften Band 165 Heft 2, 129 – 144.
54 Umweltbundesamt (2020): "…tiefengeothermischer Ressourcen". Abschlussbericht (31/2020).
55 Bracke, R. (2018): "Wärmepotentiale nutzen – Einsatz der Geothermie erleichtern". Drucksache 17/256.
56 Geologischer Dienst NRW (2018): "… Geothermie erleichtern". Drucksache 17/256.

5. Value Creation and Export Potential

Domestic added value creation

Around 71 % of energy consumption in Germany is covered by imported energy from various sources[57]. In 2018, this amounted to 63 billion euros or 1.9 % of the gross domestic product[58]. The extraction and use of domestic geothermal energy involve more interdisciplinary fields of work than other renewable energy sources. In this market, many companies provide services with great depth and breadth of value creation. The value chain establishes a link between the individual work steps required to manufacture a product and captures the value-added at the individual production stages. The final product of a value chain can be both a tangible product and a service. The products and services associated with developing and using geothermal energy can be represented as value chains for the underground and surface sectors as well as for shallow and deep geothermal energy[59]. These include different applications, e.g., in the areas of heating, cooling or electricity generation, as well as different outputs, ranging from the heat supply of a single-family house to large-scale municipal plants with thermal and/or electrical outputs in the MW range with the corresponding district heating infrastructure[60]. Overall, the expenditure for constructing and operating geothermal plants leads to versatile domestic value creation, which also benefits the local market participants. The geothermal market can be divided into 12 sectors (Fig. 9). In their entirety, these cover all industries and services required for the construction and operation of geothermal plants.

Labour market

The growing geothermal sector creates jobs in Germany for technology development and production and the construction and operation of underground and surface plants. This creates a labour market of about 5-10 full-time equivalent jobs per MW of installed capacity. Value is often added regionally, from planning to installation and operation. In the Ruhr region alone, it can already be assumed that there are at least 300 companies active in the geothermal market with about 4,000-5,000 employees. Nationwide, there were about 20,300 employees (2016) and about 1.3 billion euros in investments (2017).

Market structure

The geothermal industry in Germany has only developed perceptibly on two pillars since the turn of the millennium. On the one hand, these are young companies founded explicitly for the new market and, on the other hand, established companies in geotechnical, mining and energy technology.

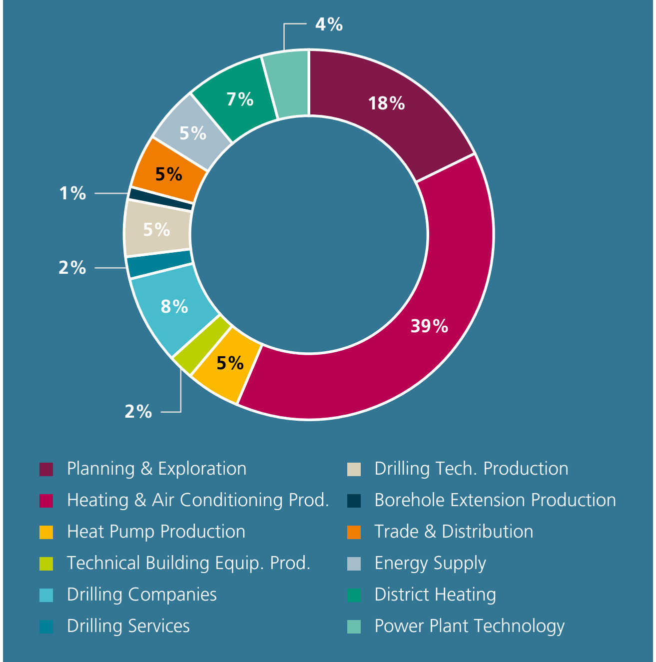


Figure 9: Share of companies in the geothermal market, example Rhine-Ruhr region[61]

57 UBA (2021): Primärenergiegewinnung und -importe auf Basis AG Energiebilanzen.
58 FZ Jülich (2019): effzett – Magazin des Forschungszentrum Jülich, 3-19.
59 Bracke et al (2008): Abschlussbericht im Auftrag der Wirtschaftsförderung Metropole Ruhr und der Stadt Bochum.
60 Modifiziert von Heumann A., Huenges E. (2018) Technologiebericht TF 1.2 T, Technologien für die Energiewende, 85-134.
61 Bracke, R. (2018): Landtag Nordrhein-Westfalen, Drucksache 17/2562 Wärmepotentiale nutzen – Einsatz der Geothermie erleichtern.

The transformation and networking of the energy system opens up new markets for suppliers of energy, mining and hydrocarbon technologies. Domestic industrial competence can thus benefit directly from structural change.

The latter have adapted their portfolios to changing demand in the move away from large, centralised fossil fuel-based generators to smaller, decentralised plants. As a result, they have expanded their business segment to include geothermal products, e.g., drilling and pumping technology (10 %), district heating (7 %) and power plant technology (4 %). Due to market growth of approximately 20,000 ground-coupled heat pump systems per year (2019; BWP), the plant engineering sector for heating and air-conditioning technology currently takes the largest share, with 39 %. This is followed by engineering, planning and exploration companies with 18 %, while the other eight sectors account for single-digit percentage shares (Fig. 9).

The type of services provided in the sectors depends on the application of geothermal energy and the output range, which extends from the heat supply of a single-family house to large-scale municipal plants. In the heterogeneity and complexity of the market, many participants also see a unique opportunity, as there is no one key technology. With its often regionally anchored and, at the same time, broad and deep value chain, the sector can hold its own relatively well economically.

The size structure of the geothermal industry is also heterogeneous: about 15 to 20 % are globally active companies with services and products for heating, cooling, power plant and mining technologies. Some of them are among the global market leaders, such as in cooling technology for geothermal power plants. However, the majority of market participants tend to be small to medium-sized. About half of the companies with up to 20 employees currently achieve an annual turnover in the geothermal market of up to 5 million euros

6. Challenges to the Expansion of Geothermal Use

Market-ready standard technology

Developing and using deep geothermal reservoirs have been a standard technology in Europe and Germany for many years. In Germany alone, 42 plants with 359 MW of installed thermal capacity and 45 MW of electrical power (2020) are safely operated.

Heat production costs

Deep geothermal energy is competitive. Assuming a flow rate of 100 kg/s per production well and an output of approx. 20 to 22 MW_{th} per doublet after transmission grid losses on a 5 km transport route up to transfer to a district heating network; this results in heat sales of 160,000-170,000 MWh/yr with an internal electricity demand of approx. 10,000 MWh per heating plant. Depending on the required drilling depth, the production costs are currently approx. 1.8 to 2.2 million EUR/MW[62] of installed capacity. Assuming a cost distribution of 60 % capital-related costs, 10 % demand-related costs and 30 % operating costs, the heat production costs are currently 25-30 EUR/MWh. Depending on the required drilling depth, the production costs are currently approx. 1.8 to 2.2 million EUR/MW of installed capacity. Assuming a cost distribution of 60 % capital-related costs, 10 % demand-related costs and 30 % operating costs, the heat production costs are currently 25 to 30 EUR/MWh. However, an indispensable prerequisite for improving the heat production costs is, on the one hand, a reduction of the exploration risk in the early phase of projects, i.e., an investment subsidy of currently approximately 40 %, and, on the other hand, comparable operating cost conditions (OPEX) to fossil and other renewable generation methods. At the same time, a critical lever lies in the scaling of the plant size: i.e., towards a large number of boreholes per heating plant, in the increase of the bulk of production rates of deep boreholes through engineering and drilling measures, and finally in the regional clustering of geothermal plants in interconnected grids to increase the plant-specific annual total load hours.

62 All information about costs and services are based on personal information and data from operators of geothermal heating plants around the South German Molasse Basin.

Scaling up to industrial scale

To roll out deep geothermal energy in the next 10 to 20 years from the regionally limited applications in southern Germany to a supra-regional, industrial scale in the clear double-digit gigawatt range (i.e., factor 100 compared to existing), a disruptive approach is necessary. Existing and needed technologies cannot be deployed in every region of Germany with guaranteed success. Therefore, there is still a need for research and development in some areas. At the same time, there is a crucial gap in the collection and availability of geological data, which is available in large quantity and quality in some parts of the country but has so far not been accessible for developing geothermal projects. This gap was recently closed by introducing the Geology Data Act (GeolDG), which creates the prerequisite for permanently providing geological data for federal and state tasks while regulating access for investors. However, in regions with insufficient geological data, these still need to be collected as quickly as possible by the state geological surveys and made immediately available.

The actors involved in the geothermal heat transition must tackle these complex challenges with a bundle of interlinked activities.

6.1 Policy

Expansion targets

Germany's heat potential from deep geothermal energy is well over 300 TWh/yr. Of this, at least 150 TWh/yr are for space heating, 20 TWh/yr for hot water supply, approx. 120 TWh/yr for industrial process heat and about 10 TWh/yr for air conditioning and process cooling. Policymakers should set ambitious expansion targets until 2025, 2030 and 2040 as soon as possible to trigger the flanking programmes and activities needed for the heat transition. It is recommended to cover at least 100 TWh/yr from deep geothermal energy by 2030 and to create the framework conditions for 20 to 25 GW of installed capacity to achieve the 50 % target of climate-neutral municipal heating (i.e., approx. 400 TWh/yr). An expansion target of 300 TWh/yr (70 GW) should be aimed for by 2040.

Regulation

In the development of the subsurface of conurbations, there are organisational and, above all, legal issues to be solved in addition to technical challenges. The environmental and groundwater protection regulations and various uses of the subsurface currently have an inhibiting effect. It is indispensable to protect people, goods and the environment. Nonetheless, regulatory law must be fundamentally adapted. The creation of suitable regulatory frameworks includes

a. delimitation of content (e.g., drinking water protection versus energetic use of saline groundwater),
b. accelerated authorisation procedures with a concentration effect (e.g., establishment of an official authorisation control system, time-based authorisation requirement, e.g., analogous to building law, elimination of interim authorisations, resource utilisation authorisation with compulsory investment after approval has been granted), as well as
c. the adaptation of partly competing statutes (e.g., spatial planning, land law, water law, as well as BBergG, BauGB, UVPG, GEG, WärmelieferVO), including
d. the designation of preferential areas in land use planning and the introduction of binding municipal heat planning[63].

A suitable legal framework must also be created for underground thermal storage facilities' construction and permanent operation. Citizen energy models for developing geothermal local heating projects can become very important, especially in the new construction sector and rural areas, and should be anchored in regulation and supported by a funding framework.

Administration

The geological services should make existing subsurface data available digitally without delay. In urban areas, they should also be commissioned with targeted geophysical exploration programmes as part of the national geological survey if the data situation is inadequate. The federal-state authorities should be instructed to designate priority areas for geothermal energy in the regional planning of the federal states, with particular attention to protecting species and nature[64]. It must be pointed out that in an area with high geothermal potential, the local hydraulic properties and thus the yield of the water-bearing strata are challenging to assess.

63 Sandrock et al. 2020.
64 https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4369.pdf

For municipal land-use planning (BauGB §5 para. 1 no. 2b), the preparation of development plans (BauGB §9 para. 1 no. 12), e.g., with a particular geothermal area, should be prioritised. For municipal land-use planning (BauGB §5 para. 1 no. 2b), the preparation of development plans (BauGB §9 para. 1 no. 12), e.g., with a particular geothermal area, should be prioritised. Under licensing law, sufficient distances between geothermal boreholes must be considered to prevent mutual interference with neighbouring mining rights holders. At the same time, it must be ensured that several neighbouring heating plants can have access to the same heating network. In addition to using the subsurface, pipeline construction across municipal boundaries must be simplified in terms of licensing law. Furthermore, administrative structures, including the geological services, must be adapted to the political goals: the massive expansion of deep geothermal use in the area requires a considerable increase in personnel resources at the licensing and monitoring authorities. In addition to capacities, the focus should also be on technical concentration.

Market incentives

The CO_2 price must become the leading market incentive tool. The heat production costs of 25 to 30 EUR/MWh for geothermal – as for most other renewable heat producers – are expected to remain above the fossil (natural gas) district heating price even after 2030. Thus, there is a need for incentivising despite the introduction of CO_2 pricing[65]. An example could be the operation of geothermal plants with a CO_2 reduction-oriented charging of operating costs (chargeable CO_2 avoidance potentials).

In the initial phase, geothermal projects often have considerable exploration risks. These are not bearable for municipal and private utilities alone. Therefore, introducing financial instruments to reduce economic risk and prevent market failure is essential. Suitable means could be, for example, insurance solutions or a revolving geothermal development fund. Both would bear the risk of exploration and initial well(s) and be linked to payback if the discovery is defined in advance. This financial instrument has been used successfully in East Africa and Latin America for several years with substantial German participation (KfW) (Geothermal Development Fund /GDF).

Considerable investments are needed to install and connect geothermal heat capacity of around 25 GW within ten years

65 Thamling et al. 2020.

Ambitious expansion targets are a prerequisite for expanding deep geothermal energy to an industrial scale. Additionally, instruments to reduce the exploration risk, concentrations under licensing law, a better regulatory framework, industry integration and training of skilled workers are crucial for the success of deep geothermal energy, and consequently for the heat transition.

and approximately 70 GW within 20 years. One gigawatt (GW) of installed thermal capacity requires the construction of up to 100 deep wells. If one calculates roughly capital-bound costs of 2.0 to 2.5 billion Euros per GW for heat generation, without distribution infrastructure, approx. 60 billion euros must be mobilised in the medium term, and approx. 170 billion euros in the long term. To this end, federal funding for efficient heat grids (BEW programme) should be substantially increased in the short term to an annual funding volume of well over 1 billion Euros, with the option of expanding this further when the market picks up.

The targeted expansion of district heating networks by 2030 will require a total investment of about 33 billion euros. Almost half of this will be spent on the expansion or extension of heating grids, 11.1 billion euros on additional plants for the generation of renewable heat and the utilisation of waste heat, and about 4.3 billion euros on the connection of new heat sources to existing grids. The funding demand for renewable district heating generation – depending on the development of future framework conditions, in particular the expected significant increase in CO_2 pricing in the heating market and the EU Emissions Trading Scheme (ETS) – is expected to decrease significantly after 2030.

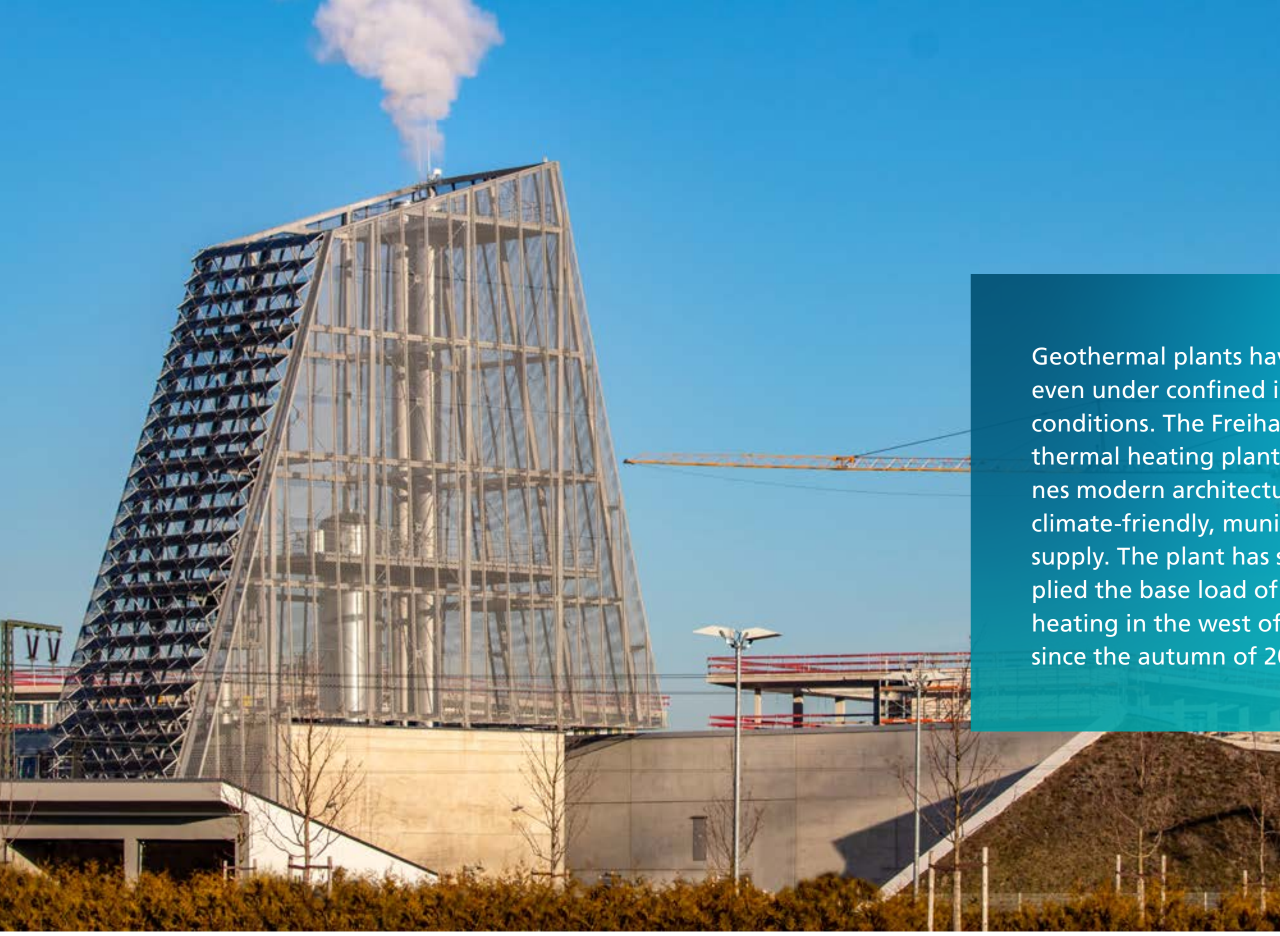
6.2 Market

Grid operators

Municipal and supra-regional energy supply companies (EVU) are facing significant challenges in transforming and expanding their grids. Due to the small amount of inner-city land required, geothermal energy can cover a substantial share on the generation side: by 2030, deep geothermal energy can feed into at least 20 % of district heating grids and, together with surface geothermal energy, cover at least 20-30 % of the municipal heating demand. However, the lead times of several years for integrating geothermal heating plants into the municipal heat supply (currently 5-7 years) require binding municipal and corporate strategies as early as possible, as well as the implementation of site-specific feasibility studies and the securing of the resource undermining the law. The risk of a stand-off with competing applicants is real and should be considered in a regulatory manner through the appropriate design of the permit fields.

In particular, the expansion and interconnection of geothermal heat infrastructures across municipal boundaries can increase the annual total load hours from 30 % to 70 % and the operating hours of heating plants from a solid 2,000 h to 6,000 h or more[66]. The buffer effect of the grid also increases the utilisation of each connected geothermal heating plant

66 Keim, M. (2020): Praxisforum Geothermie Bayern 14.10.2020.



Geothermal plants have room even under confined inner-city conditions. The Freiham geothermal heating plant combines modern architecture with climate-friendly, municipal heat supply. The plant has supplied the base load of district heating in the west of Munich since the autumn of 2016.

(in terms of the amount of energy generated per production well) and thus its economic viability due to falling heat production costs. The increase of the connection rate in dense urban neighbourhoods and the lowering of grid temperatures to 60 to 80 °C also contribute to this.

At the same time, the creation of seasonal underground storage capacities in the grid area and the development of business models for sector coupling between the heat distribution, heat storage (bidirectional load management) and the electricity side (large-scale heat pumps) are essential for the energy industry. Municipal activities to transform and expand heat grids should start at this point. In addition to municipal extraction, energy supply companies should also examine the connection of geothermal heating plants from the periphery and provide transportation routes to the inner cities. Despite the small area required for a geothermal plant, many regions and municipalities will be unable to build the necessary number of geothermal heating plants in inner-city locations.

Building and housing industry

According to the Federal Climate Protection Act 2021, the building sector must reduce annual CO_2 emissions by 43 % compared to 2020 levels by 2030. The geothermal sector already has a double-digit market share in the new building sector. It is expected that heat supply in these areas will continue to be pushed through the construction of low temperature heating grids with geothermal sources. In contrast, the housing industry faces the challenge of decarbonising the heat supply of existing properties by directing the necessary investments into construction (increasing efficiency to minimum standards through building renovation) and converting to climate-neutral supply technology. Particularly in the case of existing buildings in social housing, it is necessary to evaluate which options will lead to greater cost control. It may be that the distribution systems of the heating systems can be retained and the generation side switched from fossil to RE sources with local heating networks. Depending on the available usable temperature from local heating networks, a wide range of experiences in the energy refurbishment of existing buildings prove that the energy refurbishment of suitable building age classes can be carried out cost-effectively and makes sense compared to (partial) demolition and new construction. In particular, easy-to-implement measures such as window replacement and insulation of basement and top-floor ceilings will substantially reduce the temperature demand in buildings. The usable potential of geothermal energy could be significantly increased by reducing energy demand.

By 2025, the housing sector can convert 10 % of existing buildings to deep geothermal energy and achieve a share of 30 % in the new construction sector. By 2030, this sector can reach about half of its required greenhouse gas reductions from deep geothermal energy. In the long term, at least 30 to 40 % of the building stock can be air-conditioned geothermally.

Industrial, commercial and food production

Many industrial and commercial companies, data centres, agricultural producers and food manufacturers require temperatures between -10 °C and +200 °C for steam- and heat- and cold-based processes. The exemplary integration of geothermal energy in processes of critical industries (e.g., paper, food, chemical production) should be carried out by 2025 and publicised sector-specifically to achieve imitation effects. 0.5 to 2 GW of installed capacity in these sectors is conceivable by 2030. By 2040, geothermal generation capacity could be expanded to 10 to 14 GW for process heat and steam and to 1 GW for cooling. Key technologies here are high-temperature heat pumps or other processes for increasing the temperature level up to around 200 °C and nominal power ratings up to 50 MW.

Finance

The financial sector must primarily finance the conversion of the heat supply to renewable sources. To this end, proposals for deep geothermal projects and infrastructures must be developed over several development phases. The increased risk until the first well is drilled must be paid particular regard. Suppose a significant number of projects are to be initiated by 2025. In that case, such instruments (risk mitigation funds and insurance offers) must be realised and accepted by the market by 2023 at the latest.

6.3 Innovation and Technology

Key technologies

Consequences of geothermal expansion to a supra-regional, large industrial scale are the scale-based and organisational mitigation of project risks as well as the technology-based improvement of economic efficiency. The construction and operation of geothermal plants require geological-geophysical exploration suitable for describing the reservoir properties with characteristic values that enable the pre-dimensioning of geothermal systems. Exploration results must also be used to answer technical questions on drilling technology, mining safety and environmental impacts. It is essential to orient this exploration, so that project investments are kept low in this high-risk phase (Figure 10). A test well or initial well that is also sized so elaborately that it could be used for production shifts a large part of the high project costs into the high-risk phase[67].

Figure 10 summarises the project risks and project costs along the lifespan curve of a geothermal plant. The need for innovation and the availability of key technologies for the coming decade is particularly relevant for the project phases of reservoir exploration and development and thermal energy production and storage.

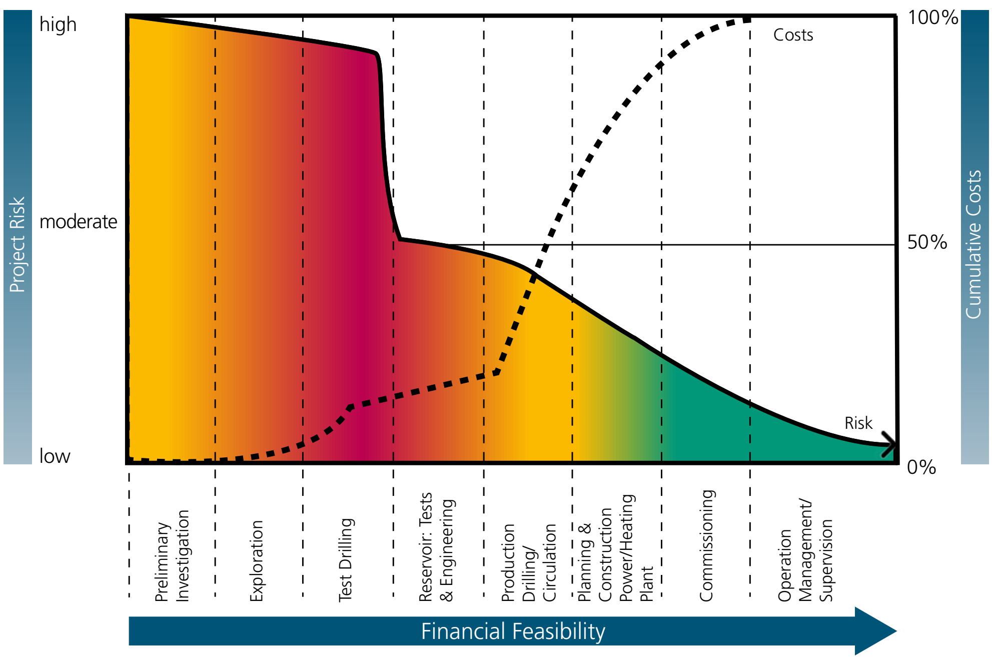


Figure 10: Development phases of a geothermal heat plant with cost progression (modified after ESMAP, Technical Report 002/12)[68].

67 Sass, I., et al. (2017): Swiss Bulletin für angewandte Geologie 21, 57-65.

68 Gehringer & Loksha (2012): Geothermal Handbook: Planning and Financing Power Generation. ESMAP, Technical Report 2012.

Key technologies address, in particular, the areas of a) underground technology, b) thermodynamic converters, c) energy infrastructures, and d) energy storage. For the development of "10-year key technologies", a need for investment and funding is derived for the following areas:

Demonstration projects

The development of demonstration projects is important for the supra-regional expansion of key technologies, as visible and successful demonstration projects can reduce reservations and create a valuable information base for further projects. To this end, the establishment and operation of approximately 20 real-world laboratories in regions with high heat demand and the broadest possible municipal and industrial applications by 2030 are recommended. In addition, a greater research infrastructure for developing key technologies needs to be established to accelerate regional learning curves and compensate for different levels of knowledge of geological conditions as quickly as possible.

Research infrastructure

The subsurface system, with its branching flow paths and physical-chemical impacts, is central to the success of a geothermal system. Only if the processes in the underground heat exchanger are identified in individual geological structures can efficient and safe reservoir management using environmentally friendly strategies be ensured. As a result, seismicity and environmental pollution can be prevented even better. In this sense, Underground Research Labs (URLs) have central importance as they shed light on the fundamental physical-chemical-biological understanding of sites with similar geological characteristics. In particular, the GeoLaB Initiative[69,70] of KIT, GFZ and UFZ enable the bridging of the investigation gap between laboratory and reservoir scale, and the metropolitan laboratory TRUDI of FhG enables the process of understanding between the reservoir and integrated energy infrastructures. Furthermore, these investigations enable scientific questions to be combined with social research in terms of participation and public acceptance in a way that is effective in the media.

69 Schill, E. et al. (2016): Geotherm Energy 4 (1), 1.
70 Schätzler, K. et al. (2020): Mining Report – Glückauf 156 (6).

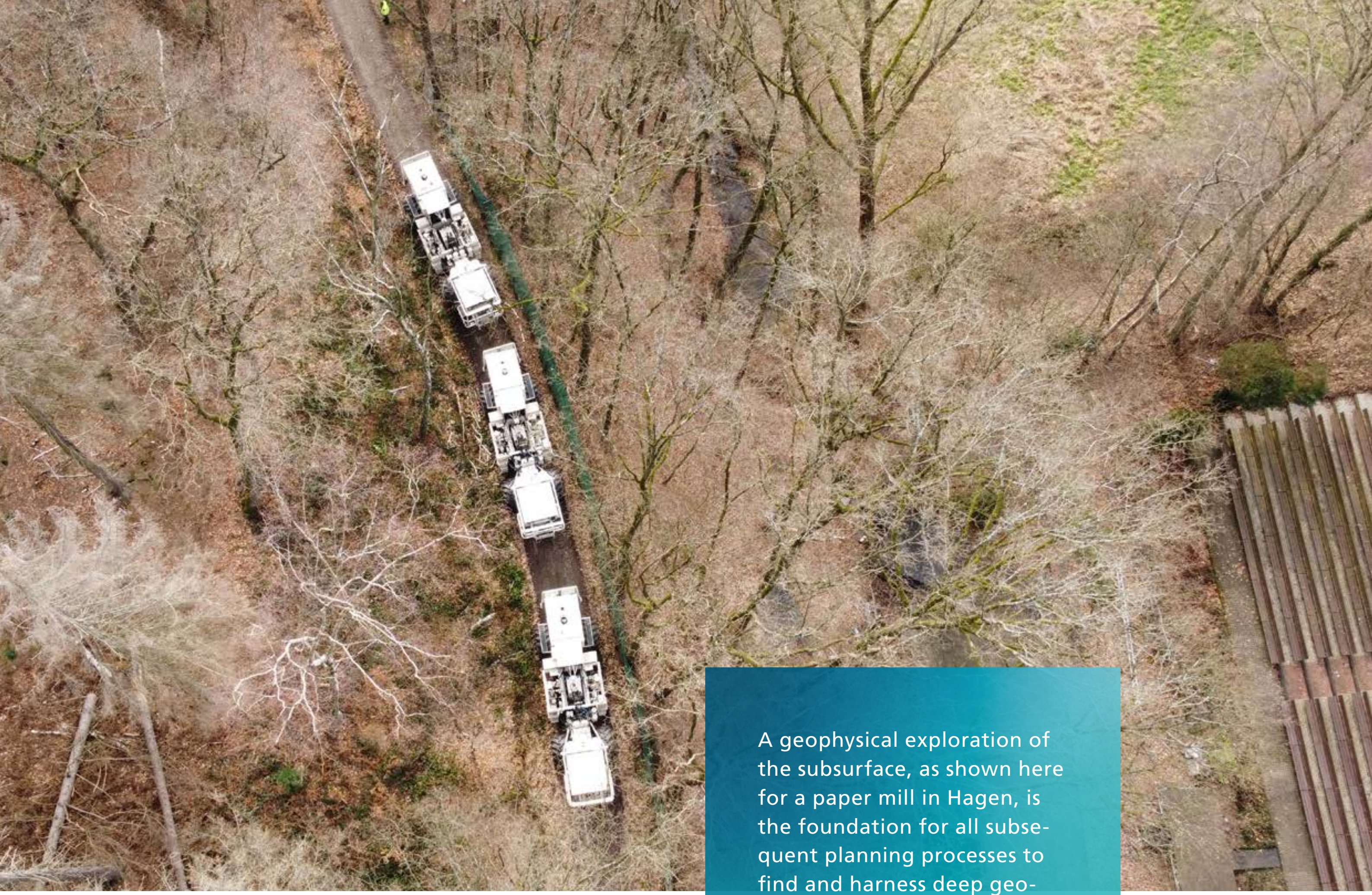
Digitalisation

Data acquisition and data synthesis, process simulations (forecasting), system optimisation through to holistic energy system analysis with connection to other energy sectors (sector coupling, digitalisation of distribution grids, intelligent linking with the electricity grid) must play a prominent role in the overall process. Digitalisation processes in geothermal energy force a close interdisciplinary and goal-oriented cooperation between the natural sciences, engineering and information sciences. Important framework conditions are formed by the FAIR principles[71] along with a close connection to the National Research Data Infrastructures (NFDI, in particular, geoinformation systems) to standardise geothermal information systems that map the complete system analysis processes mentioned above. They thus allow a quantitative evaluation of the effects of alternative solutions and map the structure and behaviour of complex systems with the areas of underground and associated integrated energy infrastructures (e.g., plant and building technology, intelligent distribution grids) in a targeted approach. At the same time, they can identify and represent possible dependencies and interactions between the areas. Digital systems in the field of geothermal use of geological space are, in connection with modern and efficient exploration and monitoring measures (intelligent measuring systems, Internet-of-Things), the only effective instruments for analysing the potential of this form of use with the aim of a sustainable energy supply in the electricity and heat sector[72,73].

Exploration

To promote the widespread expansion of geothermal plants, a reliable forecast of the geological conditions (local geology, chemical and physical fluid properties and mechanical/hydraulic rock properties) is required for many supra-regional sites and, in particular, for urban areas. Reliable forecasting requires seismic exploration – flanked by a scientific drilling programme and numerical modelling tools (e.g., from the E&P industry) as well as the integration of existing geo-information. By 2025, feasibility studies and geophysical exploration programmes for reservoirs in 20 % of major cities and towns should be underway, and by 2030 the potential of deep hydrothermal geothermal energy must be explored area-wide and the data

71 Wilkinson et al. (2016): The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data 3: 160018.
72 Rink et al. (2022): An Environmental Information System for the Exploration of Energy Systems. Geothermal Energy.
73 Signorelli, S. et al. (2004): 29th Stanford Workshop on Geothermal Reservoir Engineering, Bd. 29.



A geophysical exploration of the subsurface, as shown here for a paper mill in Hagen, is the foundation for all subsequent planning processes to find and harness deep geothermal energy – ideally supported by drilling exploration.

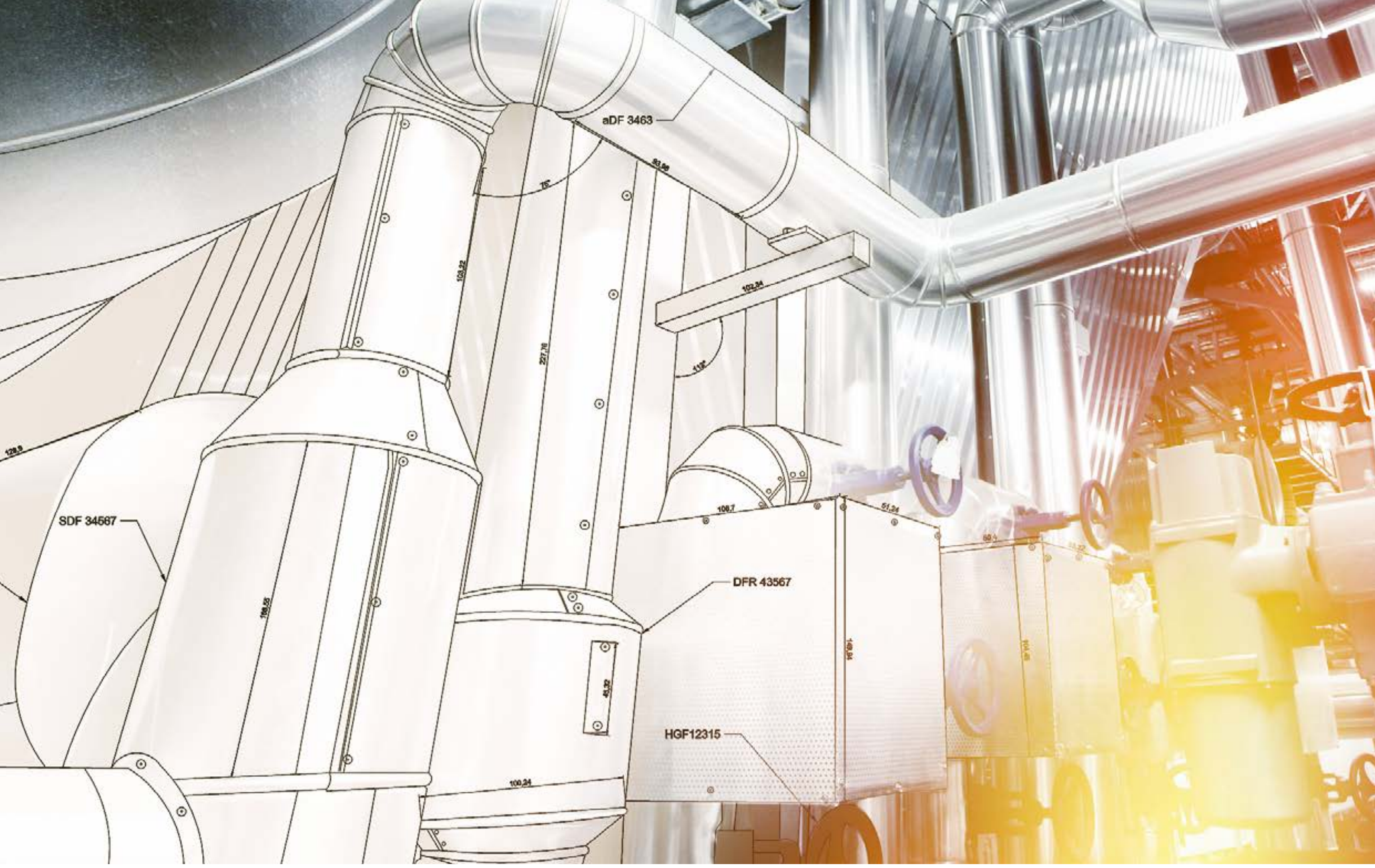
made available digitally. By 2040, the exploration of petrothermal systems in the basement and tectonically active zones in regions with large heat sinks should also be completed.

Development

Drilling accounts for the majority of the investment costs of deep geothermal projects. Due to further developments and adjustments in the drilling technology itself, in the borehole designs and the drilling sequence planning, increased production rates can be achieved in addition to considerable time and cost savings. By 2025, approaches from hydrocarbon technology would have to be tested and, if necessary, modified and transferred to geothermal applications within the framework of research projects (e.g., controlled horizontal drilling to increase the production string number and area). Medium-sized, low-emission drilling rigs (e.g., 100 to 150 t class) should be developed and made commercially available for inner-city drilling. Innovative sensor technology should monitor reservoir development in a standardised way (e.g., fibre optics-based methods, passive seismic). By 2030, these new development methods should already lead to significant cost reductions compared to the current state of the art.

In addition to well-development, new technological concepts are needed in the underground system. For example, geothermal fluids often place high demands on the choice of materials, plant design and operational management due to their often-complex chemical composition and entrained gas contents. Preventing these operational risks includes identifying suitable materials and coatings to protect against corrosion, developing inhibitors and operational strategies to prevent precipitation, and developing additives and operational strategies to control mineral precipitation. The further development of monitoring concepts is also crucial for plant operation. The observation of reservoir and operating parameters is essential to enable the introduction of regulatory measures at an early stage.

To increase the efficiency of the system technology, further development of the deep submersible pumps used for fluid pumping is required. Technical developments show that it is possible to adapt deep submersible pumps to the special requirements of geothermal applications in terms of material selection, bearing design and sensor technology. Reliable and efficient pumps must be made available for different site boundary conditions. On the production side, a competitive market for environmentally friendly submersible motor and shaft pumps must be established by 2030.



Generation and storage

When it comes to integrating deep geothermal energy into the energy system, solutions for sector coupling and storage, models for integrated energy infrastructures and digitalised operator solutions for neighbourhood supply will be needed in the next five years. Typically, the largest share of the system costs is incurred by the operation of the energy centres. Model-based strategies are required for the new construction of decentralised low-temperature heating and cooling grids, and for the dynamic transformation of existing grids from centralised to multiple, decentralised (including geothermal) heat sources, together with the associated changes in pressure, volume flow and temperature. If technically possible, existing grids should be operated at lower temperatures. If this is not possible in the primary distribution system, the possibility of disconnecting sub-distribution systems should be examined. The same applies to the integration of underground storage facilities that are fed with surplus heat from CHP, industrial processes or RE.

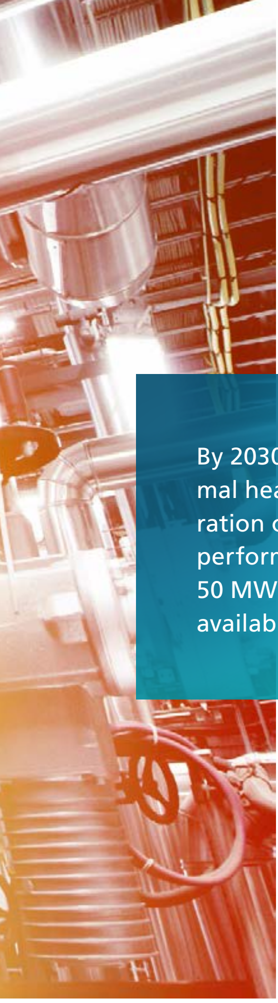
Thermodynamic converters of different types are of decisive importance for the broad use of deep geothermal energy to provide heating and cooling[74]. Large-scale heat pumps are especially needed for the use of geothermal energy for heating supply via heat grids, necessitating the development of classic heat pump processes toward larger plant capacities and their demonstration. Parallel to this, further developments in the field of high-temperature heat pumps or alternative processes for temperature upgrading to well above 120 °C are required for existing district heating networks with higher operating temperatures and, above all, for the provision of process heat.

Specifically, for industrial process heat demand, these systems must be developed and tested so that the industrially required process steam can be generated directly in the required quality. By 2025, heat pumps with temperatures of 180 °C to 200 °C should be developed on a pilot scale. Subsequently, industrial production of such heat pumps in the power class up to 50 MW should start by 2030. Innovations in thermodynamic converters are needed in the field of components (e.g., compressors, expansion elements), large-scale heat pumps (refrigerants, absorption systems, COP optimisation), system hybridisation (waste heat utilisation, coupling with other generators for renewable heat) and system flexibility (power electronics, operating modes, integration in heat and cold storage). In addition to developing and optimising appropriate heat pumps, it is also necessary to increase the efficiency of technologies for generating electricity from geothermal heat and further develop technologies for cooling from geothermal heat with lower source temperatures.

One particular area of potential for geothermal energy lies in the storage properties of the rock[75]. Near-surface systems

74 Kranz, S., Frick, S. (2013): Applied Energy, 109, 321-327.

75 Bauer et al. (2013): Environ. Earth Sci. 70 (8), 3935 – 3943).



By 2030, large-scale geothermal heat pumps for heat generation of up to 200 °C in the performance category of up to 50 MW must be commercially available on an industrial scale.

have already been realised several times as geothermal probe storage, and there is sufficient experience in dimensioning and operation. However, an impact on drinking water resources must be avoided. Medium-depth seasonal heat storage in deeper water-bearing strata (ATES) is one solution, as the saline aquifers cannot otherwise be used[76,77]. In addition, a much higher temperature level for storage is feasible there, which, together with the lower hydraulic conductivity of the layers, makes reduced losses possible.

By 2025, the integration of underground energy storage should be implemented in the legal framework of the energy system. The creation of this legal framework is the basis for the construction and permanent economic operation of underground storage facilities, including heat grid integration. Process and material science research aspects lie in corrosion, thermal and thermo-mechanical design, manufacturing technology, and system integration of heat storage facilities. Accompanying research is already addressing fluid-rock interactions, storage integrity and groundwater microbiology.

6.4 Transfer, Capacity and Acceptance

Technology transfer and capacity building

Innovation and technology development must be quickly transferred from research to industry. At the same time, the disruptive process needed for the heat transition requires a considerable increase in the capacity of geothermal technologies on the market. The necessary growth must be created within a very short period with the help of accompanying structural and economic development measures.

The combination of underground, surface and storage technologies for the geothermal energy provision of approx. 150 TWh/yr (54 GW) space heating (75%), 20 TWh/yr (3 GW) hot water (4%), approx. 120 TWh/yr (approx. 14 GW) industrial process heating (20%) and 10 TWh/yr (1 GW) cooling (1%) requires a large number of new wells. Up to 100 deep wells are needed per GW of installed capacity (assumption: 15 to 25 MW_{th} per doublet, i.e. production well and reinjection well): i.e. approx. 2,000 wells would have to be drilled by 2030 and approx. 7,000 to 10,000 wells by 2040. There is simply not enough capacity for deep drilling rigs and operating personnel, not even across Europe.

At the same time, the hydrocarbon industry in Europe is undergoing profound structural change. For capacity building, the standardisation of work processes as well as the technological competencies and professional experience of this industry should be considered at the earliest possible stage in the development of the subsurface on an industrial scale.

In the mechanical and plant engineering sector, there is also an increase in heat or cold generation plants. Assuming that a large part of the new capacities will be in the 5 to 20 MW power class, 3,500 to 14,000 geothermal heating plants or other plants for thermodynamic conversion would need to be built.

Conversion and new construction of heating networks

The transformation of local and district heating networks goes hand-in-hand with far-reaching technical adjustments (feed-in points, volume flows, pressure maintenance and temperature levels, etc.). The majority of the existing networks must be converted in terms of operational management and technical equipment. In Germany, there are 450 district heating network operators and more than 1,300

76 Schulte, D.O. et al. (2018): bbr Leitungsbau | Brunnenbau | Geothermie 69, 70-75.
77 Welsch, B. et al. (2016): International Journal of Energy Research, 40(13), 1855-1868.

individual networks with a total network length of about 25,000 km (BDEW); i.e. a district heating expansion from 112 TWh/yr to 171 TWh/yr requires more than 10,000 km of new district heating network capacity. This means that 30,000 to 40,000 km of district heating networks will have to be built or converted in the coming years. More than 25 to 30 % of these may be geothermally supplied networks. In the housing sector, a large number of local networks (local heating, local cooling) are also affected by the transformation. Of the 36.9 million dwellings in Germany, 5.2 million are supplied by district heating and 25.5 million by block and central heating, mainly with natural gas[78].

The transfer process can be strengthened by regional clusters such as the Geothermal Alliance of Bavaria, embedded in the respective innovation strategies of the federal states, and by bringing together the local actors.

Personnel requirements

To achieve the proposed goals, a substantial increase in personnel is necessary for all areas. For each MW of installed capacity, at least 5 to 10 employees are needed along the entire value chain from R&D, education and training, administration and authorities, production of surface and underground technology, plant construction, and pipeline construction to operation and maintenance and services. In the medium term, this means creating 50,000 new jobs in the academic and technical sectors. In the long term, an increase of several hundred thousand jobs in the value chain is essential.

Education programmes

Education and training must be significantly strengthened for all sectors of the geothermal industry. Education and training programmes for 10,000 to 20,000 people per year must be established to implement the outlined expansion scenarios. The development and accreditation of new training formats (“geothermal technician”) are not considered expedient. Moreover, the content of existing programmes should be supplemented and networked. Educational institutions and chambers should adapt existing curricula together. Inter-company training centres, among others, could be used for implementation. The capacities of universities must also be extended. In the short term, it will be necessary to increase recruiting abroad to meet the demand for skilled workers.

Acceptance

German legislation sets high standards for sustainability and environmental compatibility. This may result dealing with conflicts of use and legal risks. Any intervention in the subsurface also presents risks, but compared to the extraction and use of oil, natural gas, coal and nuclear fuels, these are considered to be particularly low in geothermal energy. Nevertheless, the municipal heat transition requires a visible commitment on the part of the local authorities to communicate acceptance. Municipal programmes to promote social acceptance should therefore be implemented. In this context, opportunities and risks of geothermal energy should be addressed on a knowledge-based, open and transparent manner and classified concerning the supply alternatives. This explicitly includes the effects on the labour market and the environment. Various projects have already shown how a constructive dialogue with the local population can be organised. A broader acceptance analysis, which involves not only the population but also public and private decision-makers, and the development of suitable communication strategies with the involvement of the public media, therefore appears to be fundamental.

6.5 Regional Differences in the Expansion of Geothermal Energy

For all regions, it is more or less confirmed that incentives should be given on a project- basis either to support investments or through fixed compensation rates for the energy provided. In addition to the above-mentioned needs for research, there is the need for regionally specific developments.

Deep geothermal plants in the **South German Molasse Basin** have already reached a high level of market maturity; thus, the focus here should be on project-accompanying measures for long-term monitoring, operational optimisation and cost reduction, as well as supra-regional networking (expansion of pipelines across municipal borders to form larger heating systems). In particular, the incentives through the MAP have significantly contributed to the development and are an essential prerequisite for favouring further projects. On the other hand, the potential for increasing the efficiency of geothermal systems should be investigated and their technical implementation should be further developed.

The development of deep geothermal systems in the **Upper Rhine Graben** is characterised by several prototypes indicating that the systems will be ready for the market soon. The most

78 Statistisches Bundesamt 2021.

urgent research topic, especially concerning heat supply in urban areas, is the avoidance of induced seismicity. Based on the high salinity of the waters in the ORG, the control of the thermal water cycle poses challenges such as mineral deposits and corrosion and the utilisation of further potentials such as the separation of raw materials, for example, lithium.

Deep geothermal plants in the **North German Basin** have been realised at individual sites. For a large-scale development of the North German Basin, specific approaches should be chosen and supported with demonstrations at suitable plants. Several reservoir horizons are known and should be explored over a wide area. In the federal states of BB, B, SA and MV, district heating networks are widely used as an integration platform for geothermal heat.

In the **Rhine-Ruhr region**, deep geothermal energy has only recently been systematically explored and used. Economic support measures should be initiated for the multitude of manufacturing companies in the mining and energy sectors to adapt their product portfolios and build capacity. North Rhine-Westphalia and the northern Rhineland-Palatinate are home to 35 of Germany's 81 major cities, the majority of energy-intensive industries and thus Germany's largest heat consumers and heating systems. There is a need for actions, especially concentrated on the geological survey (2D/3D seismic programmes) in these regions and on the implementation of large-scale demonstration projects, if necessary, and on a network across city boundaries.

Answers to fundamental research questions are required for comprehensive development of the reservoirs of the **basement** that can be drilled almost everywhere in Germany. Deep geothermal plants in the basement use the largest heat resource by far, but to date, they are only in operation at individual locations in the Upper Rhine Graben or planned if the geology is known. An important cornerstone for further development of these systems is the GeoLaB initiative to establish an underground laboratory of the Helmholtz Association.

The complex challenges of the heat transition supported by deep geothermal energy can only be solved collaboratively by actors from politics, market, scientific community and local authorities.

7. Roadmaps

Sector	Roadmap for ...	Activity/Indicator	2025	2030	2040+
Policy	Expansion Targets (TWh / GW)	Annual work / installed capacity for deep geothermal heat generation		**100 TWh / 24 GW**	**300 TWh / 72 GW**
	Administration	Streamline licensing practice, build up specialist staff among the authorities	**Digitised access to geodata; designation of preferential areas Permitting practice** with concentration effect	Simplified authorisation, trans-municipal heating networks	
	Market Incentives	Introduce risk management framework (RMF) to minimise exploration risks	**RMF in Operation** Funds / Insurance **Drilling programme** Increase in annual BEW production volume	Coal phase-out, **preference for renewable heat sources** (50% municipal heat)	
	Regulation	Reform of mining and water law approval; feed-in tariffs; heat supply regulation; grid efficiency	**Avoidance costs as a guiding tool** for regulation, **legal framework** for construction and permanent use of **underground storage facilities**	**Support programme for citizen energy models**	**Transport routes** for heat from the peripheries to the inner cities
Market	Energy Industry	Transformation of district heating networks	**Business model development; transformation studies** taking **deep geothermal** into account, expansion of low-temperature grids.	Deep geothermal feeds into **20%** of district heating networks	**Temperature reduction** to 60 to 80 °C from 30% in the existing grids.
		Municipal heat	**Hybrid systems** (sources of complementary temperatures, use of grid-related sources, such as gas)	Geothermal (deep + shallow) **covers 20 to 30% of municipal heat demand**	30 to 40% geothermal; coupling with the power sector
	Industry and Food Production	Industrial processes < 200 °C/ Agricultural industry < 50 °C	Model coupling of deep geothermal energy into industrial processes	**0.5 to 2 GW installed capacity** (e.g., each in paper, food, chemicals, etc.)	**0 to 14 GW generation capacity for process heat** and ~1 GW installed for cooling from deep geothermal
	Construction and Housing Sector	Heat supply for neighbourhoods, new construction and building refurbishment / Construction and transformation Low temp heat networks on deep geothermal	10% of existing buildings converted to deep geothermal energy; 30% in new buildings	20% GHG reduction through deep geothermal	30-40% of the building stock geothermally air-conditioned
	Financial Sector	Financing deep geothermal over several investment phases	Risk management framework (RMF)		

Sector	Roadmap for ...	Activity/Indicator	2025	2030	2040+
Innovation & Technology	Exploration	Exploration technology / geophysics / data management	Integrated model-based planning tools, exploration programme Reservoirs in urban areas	Deep geothermal hydrothermal area-wide exploration	Exploration of petrothermal systems
	Development	Innovative drilling and reservoir technologies	"**City drilling systems** (100 to 150 t)", **drilling programme**, monitoring systems, 3D mapping of the exploitable subsurface.	**Cost reduction through innovation**	
		Innovative drilling technologies (standardised multi-lateral drilling) and reservoir engineering (multi-stage stimulation).	Automation and digitalisation	Competitor market for borehole pumps established	
		Monitoring and operation of underground / above ground			
	Generation & Storage	System solutions through sector coupling and underground storage	**Integrated, digitalised operator solutions** for urban spaces	**20 real laboratories** in operation in regions with high heat demand	
		Large-scale heat pumps for municipal and industrial requirements	**Prototype development** of 180 to 200°C heat pumps	**Industrial production** of high-temperature heat pumps at 10 to 50 MW	
Capacity & Acceptance	Technology	Underground / Surface	Development of drilling and grid capacity	**> 2,000 doublets** at 10 MW_{th} each	7,200 to 10,000 doublets
	Personnel	Provision of personnel for R&D / technology / production / construction / operation	Approx. 50,000 people are trained technically & academically	Education programmes established for more than 10,000 people / year	more than 100,000 jobs
	Education Programmes	Curricula for craft, technical and academic professions	Adaptation training and further education programmes		
	Acceptance	Management of site-specific factors (communication, acceptance, finances, operational safety, infrastructures)	**Municipal programmes** to promote social participation and positive marketing	**Citizen energy models** for geothermal heat established at municipal level	

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Prof. Dr. Rolf Bracke
Fraunhofer Research Institution for Energy Infrastructure and Geothermal Energy (IEG)
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Prof. Dr. Ernst Huenges
Helmholtz Centre Potsdam German Research Centre for Geosciences (GFZ)
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Dr. Isabella Nardini, Fraunhofer IEG

Editorial monitoring

Kosta Schinarakis, Fraunhofer IEG

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GFZ Helmholtz Centre Potsdam

KIT Karlsruhe Institute of Technology

UFZ HELMHOLTZ Centre for Environmental Research