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Geothermal Energy Use in Germany, Country Update 2015-2019

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ABSTRACT

This country report update (2015-2019) will give an overview of the geothermal energy use in Germany. It covers geothermal power production, direct use applications as well as geothermal heat pump units for heating and cooling.

At the end of 2018, about 190 geothermal installations for direct use of geothermal energy were in operation in Germany. This number includes facilities for district heating and thermal spas, the latter often in combination with space heating. In addition, at Kirchweidach (Bavaria) a greenhouse is heated by geothermal energy that substitutes fossil fuels.

The installed geothermal capacity of these facilities amounts to 406.3 MW_{th} with a geothermal heat production of 5,378.6 TJ in 2018. District heating plants accounted for the largest portion of the geothermal capacity with 346.2 MW_{th} and a heat production of 3,634.9 TJ.

Geothermal electricity generation in Germany is based on the use of binary systems (Kalina cycle or ORC). This allows power production even at temperatures of 100 °C. At the end of July 2019, ten geothermal plants with an installed capacity of 43.05 MW_{el} fed electricity into the German grid. The geothermal power production in 2018 summed up to a total of 165.6 GWh.

Due to favourable geological conditions, geothermal district heating and power plants are mainly located in the Molasse Basin in Southern Germany, in the North German Basin, or along the Upper Rhine Graben.

In addition to installations using “deep” geothermal energy, numerous small- and medium-sized decentralised geothermal heat pump units are in use for heating and cooling of individual houses and office buildings. In the last years, the sales figures of heat pumps have increased again. 84,000 heat pumps were sold in 2018, with a share of about 30% (23,500) for geothermal systems (brine and water systems). At the end of 2018, 382,000 geothermal heat pumps were running successfully in Germany and supply renewable heat mostly for residential buildings. All installed geothermal heat pumps have a thermal output of about 4,400 MW_{th} in total and provided 23,760 TJ of renewable heat in 2018. The share of near-surface geothermal systems combined with a heat pump reached about 1.1% of the total heat demand (private households) in Germany.

1. INTRODUCTION

The majority of geothermal projects worldwide is located in geological systems with convection dominated heat transport such as magmatic arcs or large scale active faults (e.g. plate boundaries) (Moeck, 2014). Germany, with its conduction dominated heat transport systems, lacks natural steam reservoirs which can be used for a direct drive of turbines. Thus, geothermal power generation is based on the use of binary systems, which use a working fluid in a secondary cycle (ORC or Kalina cycle). Hydrothermal reservoirs with temperatures and hydraulic conductivities suitable for power generation can be expected and are already utilised particularly in the Upper Rhine Graben as an active deeply rooting fault system and the Alpine Molasse Basin as an orogenic foreland basin (Agemar et al., 2014a, b; Moeck, 2014). A successful development of geothermal technologies enhancing reservoir productivity from tight sedimentary and crystalline rocks (EGS) would change the situation in Germany fundamentally facilitating geothermal energy as an option in regions without hydrothermal resources.

However, the necessary implementation of the heat transition (referred to as *Wärmewende*) in Germany shifts the focus to geothermal heat production. In contrast to fossil fuels, geothermal heat in place can be used over a large depth and temperature range by a whole variety of technologies. Due to this scalability of geothermal applications, depending on the heat demand there is a huge potential for the development of geothermal utilisation. With the *Wärmewende* in Germany, we recognize the scalability of geothermal technology as the potential of geothermal use rather than individual geologic formations. Effectively, a broad range of the geothermal gradient from shallow to medium deep account for the installed geothermal capacity in Germany.

At the end of 2018, 29 geothermal plants for district heating and/or power generation were in operation in Germany and several new plants are under construction or in the planning phase. The discovery of deep hot aquifers has led to a vivid project development especially in Southern Germany. Current projects focus on the Bavarian part of the Alpine Molasse Basin, where karstified Upper Jurassic carbonates provide a suitable aquifer of several hundred meters thickness (Fig. 1). Some projects are also in operation or under development in the Upper Rhine Graben, which is another region of elevated hydrothermal potential. Above-average geothermal gradients make this region especially interesting for the development of electricity projects.

This paper describes geothermal reservoirs and probable resources followed by the status of geothermal energy use in Germany. Different use categories such as district and space heating or thermal spas, as well as heat pumps and their contribution to the geothermal heat supply are allocated. Furthermore, governmental support for geothermal projects is outlined and future perspectives of geothermal energy use in Germany are discussed.

2. GEOTHERMAL RESOURCES

Geothermal resources applicable for geothermal power production and heat use in Germany were investigated in several studies and contributions to European geothermal atlases (Haenel and Staroste, 1988, Hurter and Haenel, 2002, Jung et al., 2002, Paschen et al., 2003). Paschen et al. (2003) suggested in their study on the potential for geothermal power generation the preparation of a digital atlas of geothermal resources in Germany. From 2005 on, the Geothermal Information System GeotIS (www.geotis.de) was developed and established as an open-access geothermal atlas (see 2.2) (Agemar et al., 2014a). The information system provides a variety of data collections on deep aquifers suitable for commercial geothermal exploitation. Furthermore, map and data compilations of regions with indicated hydrothermal resources and with inferred resources for enhanced geothermal systems (EGS) were published by Suchi et al. (2014) in a study about the competing use of the subsurface for geothermal energy and CO_2 storage. The resulting maps of that study are also available in GeotIS.

Although a great theoretical potential for geothermal power generation is attributed to EGS (Paschen et al., 2003), the commercial project development to date focuses on hydrothermal resources in sedimentary systems. The most important geologic systems hosting proven geothermal reservoirs in a depth greater than 1,000 m in Germany are the North German Basin, the South German Molasse Basin, and the Upper Rhine Graben (Fig. 1).

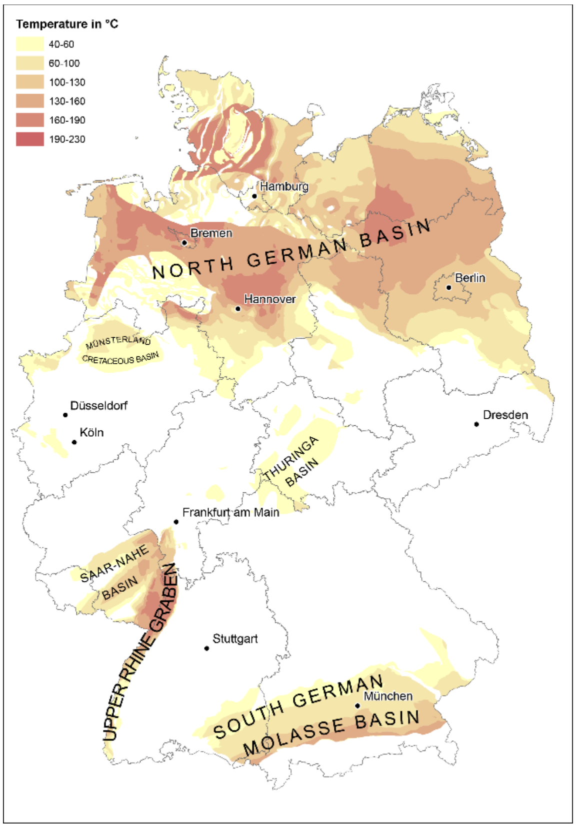

Figure 1: Regions with hydrothermal resources in Germany (inferred and indicated) and associated temperature ranges (map adapted from Suchi et al., 2014).

2.1 Regions with Hydrothermal Resources

2.1.1 The North German Basin

The North German Basin (NGB) is the central part of the Central European Basin. The thickness of its present-day sediment fill ranges from 2 to 10 km. Salt tectonic movements of the Upper Permian Zechstein evaporites are responsible for the intense and complex deformation of the overburden Mesozoic and Cenozoic formations (Franke et al., 1996, Kockel, 2002). Affected by these salt tectonics, the geologic successions vary in depth and thickness which lead to strong variations of temperature and energy content of the individual geothermal resources on a regional scale (Agemar et al., 2014a).

The Mesozoic successions of the NGB consist of siliciclastic rocks and carbonates with evaporitic intercalations. Aquifers of high permeability are the main horizons of interest for geothermal use in this region. Porous sedimentary aquifers suitable for geothermal utilisation are defined by a minimum aquifer thickness of 20 m, a porosity > 20%, and a permeability > 250 mD (Rockel et al., 1997). Several formations contain sandstone strata which are expected to meet these requirements (Fig. 2). Potential reservoir rocks with temperatures suitable for geothermal use were identified primarily in Mesozoic sandstone units (Hurter and Haenel, 2002, Feldrappe et al., 2008). Hitherto, geothermal exploration in the NGB concentrated predominantly on the Rhaethian Sandstones in the eastern part of the North German Basin (Upper Triassic Contorta and Postera sandstone) which are used successfully by geothermal plants at Neustadt-Glewe, Neubrandenburg, and Waren. Hydrothermal potential is also attributed to the Palaeozoic Rotliegend sandstones, while the underlying volcanites of the Rotliegend formation have considerable EGS potential (Jung et al., 2002).

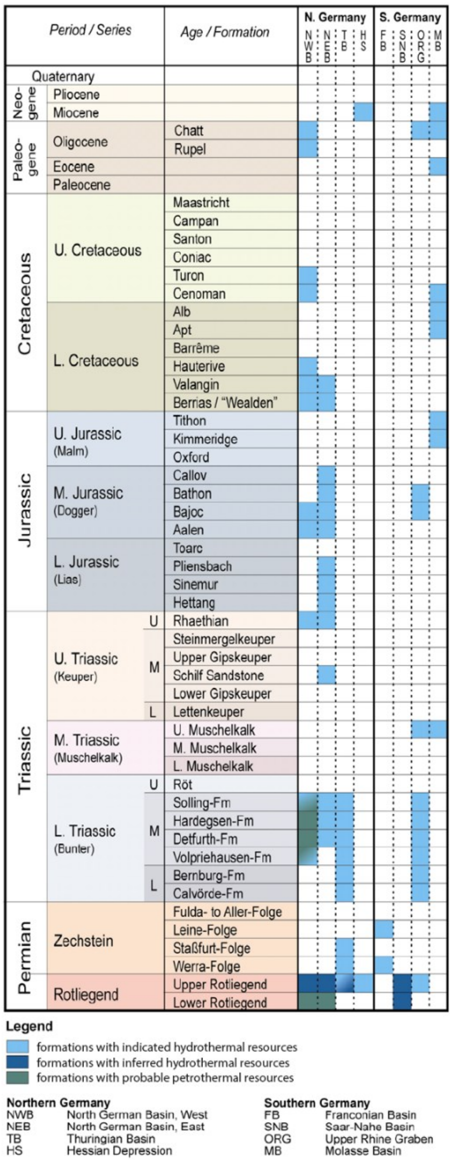

Figure 2: Stratigraphic units of interest for deep geothermal energy use (table adapted from Suchi et al. (2014), data for CO_2 storage omitted).

2.1.2 The South German Molasse Basin

The Molasse Basin in southern Germany is an asymmetrical foreland basin associated with the formation of the Alps. It extends over more than 300 km from Switzerland in the Southwest to Austria in the East. The basin fill is made up mainly by Tertiary Molasse sediments, Cretaceous, Upper (Malm) to Middle (Dogger) Jurassic and Triassic sediments (StMWIVT, 2012).

The Malm (karstic-dolomitic fractured carbonate reservoir of the Upper Jurassic) is one of the most important hydrothermal energy reservoirs in Central Europe because the aquifer is highly productive and present throughout almost the whole Molasse Basin. The aquifer´s geothermal potential and its hydraulic properties were subject to intense R&D activities (e.g. Frisch et al., 1992, Birner et al., 2012). The reservoir fluid of freshwater quality is particularly suitable for economic geothermal utilisation since corrosion effects are minimal and scaling effects are manageable.

Due to the southward deepening and wedge-shaped geometry of the basin, reservoir temperatures and depth of the Malm reservoir increase towards the Alps from 40 °C in the North to more than 160 °C in the South of the basin near the Alpine Molasse. Thus, district heating plants can be found in the northern part of the basin while combined heat and power plants are located further in the South. Temperatures suitable for power generation are reached south of Munich where several power plants are in operation.

Besides the Malm aquifer, further sedimentary layers were identified as probable aquifers for direct use of geothermal energy (Tertiary Burdigal, Aquitan and Chatt sandstone, and Baustein and Ampfinger beds, Cretaceous Gault and Cenoman sandstones, and Upper Muschelkalk) (StMWIVT, 2012). Some of the aquifers provide thermal fluids (brine) for spas in Bavaria and Baden-Württemberg.

2.1.3 The Upper Rhine Graben

The Upper Rhine Graben belongs to a large European rift system which crosses the Northwestern European plate (e.g. Villemin et al., 1986). Between 30 and 40 km wide, the graben elongates from the Jura Mountains near Basel, Switzerland, to Frankfurt, Germany. The graben was formed by repeatedly reactivation of complex fault patterns. Crustal extension in the Tertiary 45-60 Ma ago formed depocenters along a pre-existing WSW-ENE fault trend associated with up-doming of the crust-mantle boundary and magmatic intrusions in 80-100 km depth (Pribnow & Schellschmidt, 2000). The induced thermo-mechanical stresses result in extensional tectonics with a maximum vertical offset of 4.8 km. The graben evolution changed from Oligocene on from extension to dextral strike-slip and related local uplift, subsidence and finally sinistral strike-slip from Pliocene on up to date (e.g. Schumacher, 2002).

Major exploration targets for geothermal projects in the Upper Rhine Graben are the Upper Muschelkalk and Bunter formations in combination with fault zones. Further indicated or inferred geothermal resources are in the Hydrobien and Grafenberg strata (both Tertiary), Hauptrogenstein (Jurassic), and Rotliegend (Permian) (Hurter & Haenel, 2002, Jodocy & Stober, 2008).

2.2 Web-based open access Geothermal Information System (GeotIS)

In order to better understand the range of geologic settings hosting geothermal resources, subsurface data are collected, analysed, interpreted and provided by the Leibniz Institute for Applied Geophysics (LIAG) through the Geothermal Information System (GeotIS) (Agemar et al., 2014a), funded by the German Government. LIAG realised the project in close collaboration with several research partners. Besides the research focus, the practical relevance of GeotIS is to minimize the exploration risk of geothermal wells and to improve the quality of planning data for geothermal projects. GeotIS is designed as a digital information system which is available free of charge as an open-access data base (http://www.geotis.de).

GeotIS provides information and data compilations on deep aquifers in Germany relevant for geothermal exploitation. It includes data of the South German Molasse Basin, the Upper Rhine Graben, and the North German Basin. The internet based information system satisfies the demand for a comprehensive, largely scale-independent form of a geothermal atlas which is continuously updated. GeotIS helps users to identify possible geothermal resources by visualising temperature, hydraulic properties, and depth levels of relevant stratigraphic units (Agemar et al., 2014a). A sophisticated map interface simplifies the navigation to all areas of interest. Additionally, essential information of all geothermal installations in Germany is provided including annual statistics on installed capacities and energy produced.

3. STATUS OF GEOTHERMAL ENERGY USE

The German Government supports the development of geothermal energy by project funding, market incentives, credit offers as well as offering a feed-in tariff for geothermal electricity. However, progress in the development of geothermal energy lags behind the development of other renewables although there are good conditions for heating plants and also for power production at several locations (Fig. 1). For example, especially in southern Germany, a number of new projects have been realised and further developments are being planned.

Geothermal power plays only a marginal role in the German electricity market (Tab. 1; BMWi, 2019a). Its share in installed capacity and gross electricity production is only 0.019% and 0.025%, respectively. The development of geothermal electricity in Germany is rather slow.

Table 1: Present and planned production of electricity

	Geothermal		Fossil Fuels		Hydro		Nuclear		Other Renewables (specify)[1)]		Total[2)]	
	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr
In operation	41.7*	165.6#	83,700**	317,200#	10,300**	16,900#	11,400**	76,100#	106,000**	205,300#	219,342**	648,700#
Under construction in December 2019	4.5											
Funds committed, but not yet under construction in December 2019												
Estimated total projected use by 2020	46.2											

[1)] Wind, photovoltaics and biomass; [2)] includes waste and other; * as at July 2019; ** data for 2017; # data for 2018 (source: BMWi, 2019a; Geotis, 2019);

Geothermal heat is utilised in about 190 larger installations using hydrothermal resources. Thermal spas are the most widespread form of deep geothermal heat utilisation. However, the number of larger district heating plants is growing continuously. They presently account for about 68% of the deep geothermal heat production, with an upward tendency.

Besides deep geothermal utilisations, numerous geothermal heat pumps for heating and cooling office buildings and private houses contribute the major portion to geothermal heat use in Germany.

3.1 Geothermal Power Production

Since the last country update in 2015 four new geothermal power plants were commissioned in Germany: the 4.3 MW_{el} plant in Grünwald/Laufzorn (October 2014), the 5.5 MW_{el} plant in Traunreut (2016), the 4.3 MW_{el} plant in Taufkirchen (2018), and the 3.6 MW_{el} plant in Holzkirchen (2019) (all located in the South German Molasse Basin). However, the 3.36 MW_{el} geothermal plant in Unterhaching was shut down end of 2017. Therefore, the installed geothermal capacity in Germany showed only a small growth and reached about 43 MW_{el} end of July 2019 (Tab. 2). Electricity production amounted to 165.6 GWh in 2018.

At one site (Kirchweidach in Bavaria) it is planned to expand the existing heating plant with a small power unit. In Garching a. d. Alz drilling of two boreholes is completed and first tests point to a possible electrical capacity of 4.5 MW_{el}.

Table 2: Present and planned production of electricity

Locality	Power Plant Name	Year Com-missioned	No. of Units	Status[1)]	Type of Unit[2)]	Total Installed Capacity	Total Running Capacity	Annual Energy Produced 2018	Total under Constr. or Planned
						MWe[3)]	MWe[4)]	GWh/yr	MWe
Bruchsal		2010	1		O	0.55	0.44	0.035	
Dürrnhaar		2012	1		B	6.0	6.0	36.0	
Grünwald/Laufzorn		2014	1		B	4.3	4.3	16.62	
Holzkirchen		2018	1		B	3.6	3.6	0	
Insheim		2012	1		B	4.8	4.8	21.0	
Kirchstockach		2013	1		B	6.0	6.0	30.0	
Landau		2007	1		B	3.0	1.8	7.718	
Neustadt-Glewe		2003	0	R	B	na	na	na	
Sauerlach		2013	1		B	5.0	5.0	28.0	
Simbach-Braunau		2010	0	R	B	na	na	na	
Taufkirchen		2018	1		O	4.3	4.3	1.0	
Traunreut		2016	1		B	5.5	5.5	25.2	
Unterhaching		2009	0	R	O	na	na	na	
Garching a. d. Alz		under constr.							4.5
Total						43.05	41.74	165.573	4.5

[1)] R = retired; [2)] B = binary (rankine cycle), O = other (Kalina); [3)] electrical installed capacity as at July 2019; [4)] electrical capacity actually up and running as at July 2019 (source: Geotis, 2019);

3.2 Centralised Installations for Direct Use

In Germany, common deep geothermal utilisations for direct use are district heating plants or combined heat and power plants (CHP), thermal spas, and space heating. At present, about 190 geothermal installations of these types are in operation in Germany (Fig. 3, Tab. 3 & 5).

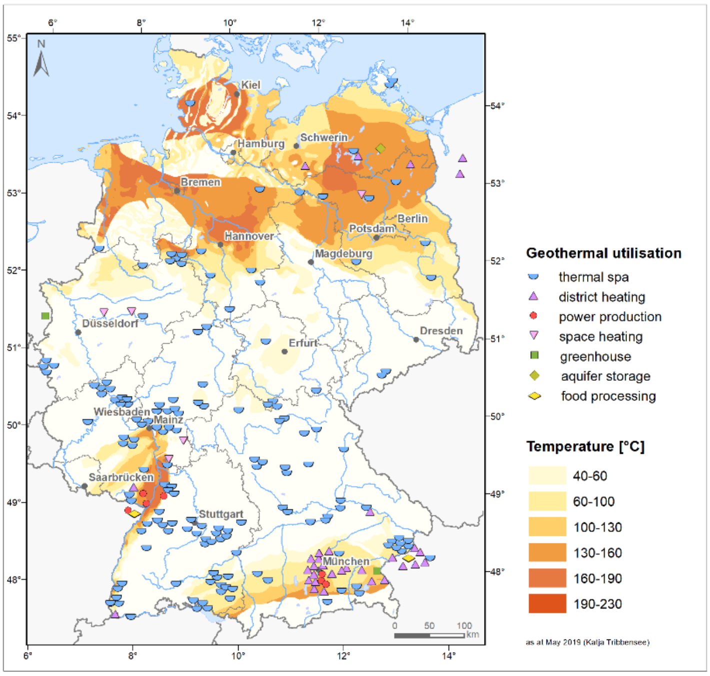

Figure 3: Sites of deep geothermal utilization in Germany and neighboring countries. The background colors represent predicted temperature ranges of the respectively deepest identified geothermal resources in sedimentary or volcanic rocks (map generated in GeotIS, 2019).

Geothermal well doublets consisting of a production and an injection well are typically used for district heating, while spas only need a single well for standard operation. Furthermore, five deep borehole heat exchangers are in operation in Germany: Arnsberg with a total depth of 2,835 m heating a spa, Prenzlau (2,786 m, used for district heating), Heubach (773 m, providing heat for industry), Landau (800 m, for space heating) and Marl (700 m, for local heating). Also the use of mine water is becoming more and more interesting with regard to the heat transition in Germany.

At end of July 2019, the geothermal installed capacity of direct heat use applications was 406.3 MW_{th}. 26 district heating and combined heat and power plants accounted for the largest portion of the geothermal capacity with about 346 MW_{th} (Tab. 3 & 5).

Table 3: Utilisation of geothermal energy for direct heat (other than heat pumps)

Locality	Type[1)]	Maximum Utilization					Capacity[2)]	Annual Utilization[3)]		
		Flow Rate	Temperature (°C)		Enthalpy (kJ/kg)			Ave. Flow	Energy	Capacity
		(L/s)	Inlet	Outlet	Inlet	Outlet	(MWt)	(L/s)	(TJ/yr)	Factor
160 thermal spas	B	-	-				56.8	-	1,708.56	0.95
Arnsberg Erlenbach 2	H	20	49				0.35	3	7.56	0.68
Bochum Zeche Robert Müser	H	-	20				0.4	22	4.32	0.34
Heubach	H	-	-				0.09	5	-	-
Neuruppin	H	3.7	56				1.4	3.2	2.99	0.07
Weinheim	H	10	63.5				1.1	9	20.34	0.59
Aschheim	D	84.7	85.9				10.7	-	232.89	0.69
Bruchsal	D	28	123				5.7	-	-	-
Erding	D	48	63				10.2	-	97.75	0.3
Freiham	D	110	89.4				13.0	-	295.2	0.72
Garching	D	100	74				7.95	-	110.52	0.44
Grünwald/Laufzorn	D	132	127				40.0	90	315.92	0.25
Holzkirchen	D	65	155				24.0	55	144.0	0.19
Ismaning	D	85	78				7.2	65	115.2	0.51
Kirchweidach	D	80	122				30.6	-	318.06	0.33
Landau	D	-	159				5.0	-	3.32	0.02
München-Riem	D	85	95.5				13.0	-	259.2	0.63
Neustadt-Glewe	D	35	97				4.0	-	47.58	0.38
Poing	D	100	76.4				9.0	85	121.68	0.43
Prenzlau	D	3.33	55				0.15	3.33	1.33	0.28
Pullach	D	93	104				16.0	86	222.12	0.44
Sauerlach	D	110	140				4.0	-	28.8	0.23
Simbach-Braunau	D	90	80.5				9.0	70.7	166.78	0.59
Straubing	D	31.4	36.5				2.1	17.5	10.44	0.16
Taufkirchen	D	120	133				40.0	120	161.64	0.13
Traunreut	D	168.8	114.2				12.0	126	113.04	0.3
Unterföhring I	D	75	86				10.0	-	75.24	0.24
Unterföhring II	D	90	-				11.3	-	125.28	0.35
Unterhaching	D	140	123.3				38.0	140	428.04	0.36
Unterschleißheim	D	93.3	78				8.0	-	143.48	0.57
Waldkraiburg	D	80	106.9				14.0	-	88.2	0.2
Waren	D	17	63				1.3	17	9.15	0.22
TOTAL							**406.3**		**5,378.6**	

[1)] B = Bathing and swimming (including baleology), H = Individual space heating (other than heat pumps), D = District heating (other than heat pumps); [2)] as at July 2019; [3)] in 2018 (source: GeotIS, 2019);

Altogether, the installed capacity of deep geothermal heat use in Germany shows a considerable increase from about 160 MW_{th} in 2010 to 336.6 MW_{th} in 2015 to 406.3 MW_{th} end of July 2019. Heat production by deep geothermal utilisation rose from 2,577.6 TJ in 2010 to 3,996 TJ in 2015 to 5,378.6TJ in 2018 (GeotIS, 2019).

Since the last country update in 2015 the development of geothermal direct use applications is ongoing and four heating plants went into standard operation (Freiham, Taufkirchen and Unterföhring II in 2016, as well as Holzkirchen in 2018; see Tab. 3). In Unterföhring, for example, for the first time in Germany an existing geothermal doublet has been expanded by two more wells and a second heating station, leading to an increase of geothermal capacity from 10 to 22 MW_{th}.

The development of direct heat use from geothermal energy is still ongoing. One example is the vision of the Stadtwerke München to supply the district heating network of the city completely with renewable energies by 2040. Geothermal energy shall act as major contributor to achieving this goal. For this purpose, a total of six wells is drilled from one site in the Munich inner city. As at July 2019, four of the six wells have been successfully completed.

Development also continues in the North German Basin. The first well of the medium deep project in Schwerin has been finished and exceeded expectations (as at March 2019). When finished, heat will be fed into a district heating network.

3.3 Geothermal Heat Pumps

Geothermal heat pumps reached the German market, after a first peak in the 1980s, with the beginning of the 2000s. The systems are mainly used for heating residential buildings and are especially installed in new buildings. However, there are also large-scale geothermal heat pump installations used for heating and cooling commercial buildings (offices, industry) within the same system.

The most common systems are borehole heat exchangers or horizontal heat collectors (brine/water systems). The share of groundwater systems with two or more wells (water/water systems) is less than 15% of all geothermal heat pumps. Other options - like activated foundation piles or direct vaporiser probes - have only a small share in the market. Much larger systems (several hundred kW) represent the top of the market. The average capacity of the installed and running heat pumps in Germany decreases since the beginning of the 2000s according to the energetic standards of new build houses.

The following market data is mainly based on the study *Analyses of the German heat pump market* (Born et al., 2017). The general aim of the study was to evaluate the amount of renewable heat that is provided by heat pumps in Germany.

For the calculation of the amount of renewable heat, the following input parameters of installed and running heat pumps in Germany are relevant:

- the sales figures of geothermal heat pumps and the lifetime of the heat pumps,
- the average coefficient of performance (COP) and the average seasonal performance factor (SPF),
- the average capacity & the average full load hours per year.

3.3.1 Sales Figures and Lifetime of Geothermal Heat Pumps

The German Heat Pump Association (BWP) and the Federation of German Heating Industry (BDH) gather each year the sales figures of geothermal as well as air heat pumps in Germany (Fig. 4).

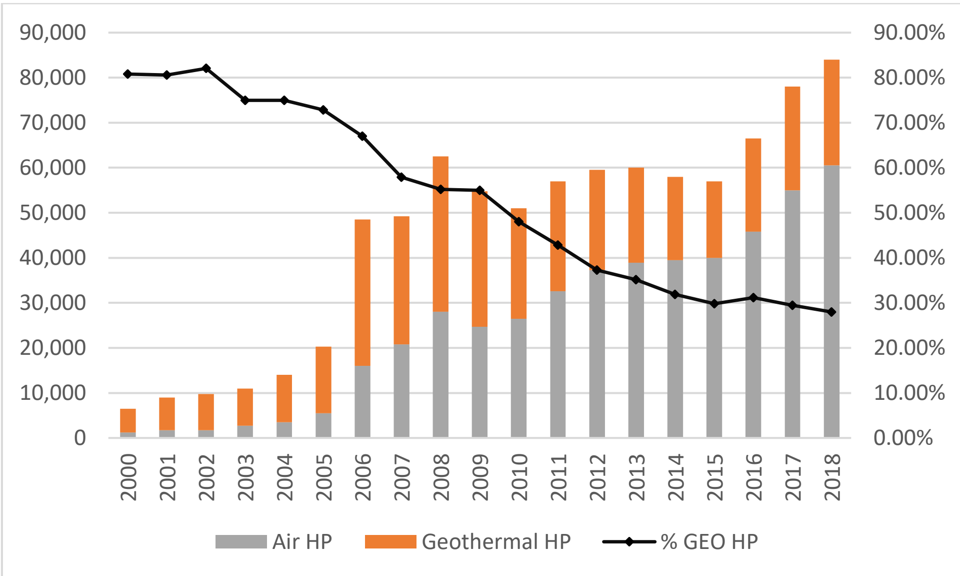

Figure 4: Development of sales figures for heat pumps in Germany (after annual data from BWP&BDH, 2013 & 2017, latest BWP&BDH, 2018).

Between 2008 and 2015 the sales figures of all heat pumps stayed on a relatively constant level (50,000 to 60,000 units per year), before the sales increased and reached the highest level of 84,000 units sold in 2018 (Fig. 4). Within the same time, the market share of geothermal heat pumps decreased from more than 50% to less than 30% in 2018 with about 23,500 geothermal heat pumps sold. Although sales of geothermal heat pumps have increased again since the last German country report (Weber et al., 2015), air heat pumps are still the dominant type of system on the market.

The increasing sales figures of geothermal heat pumps are primarily due to the changed funding conditions of the Federal Government's so-called market incentive programme. For the first time, it is possible to get subsidies of up to €6,750 for the use of a geothermal heat pump in existing buildings.

Since heat pumps are used successfully in Germany for more than 20 years, there is a correspondingly high number in operation. For the calculation of the field inventory in Germany, it is necessary to imply a function for the typical lifetime of heat pumps to compare them with the annual sales figures. A simplified service life curve is assumed for the calculation (cp. Fig. 5).

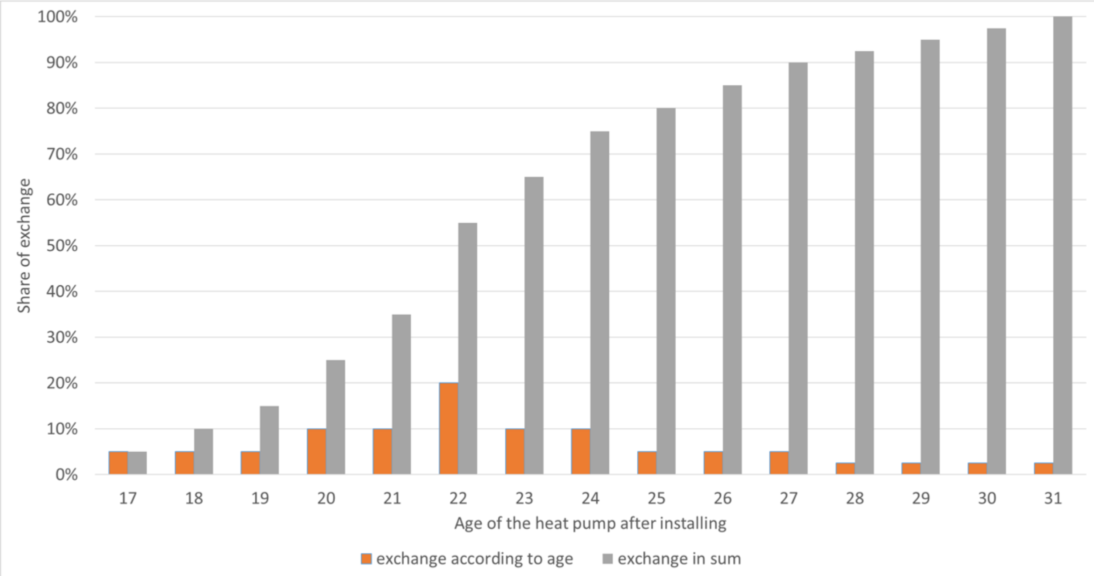

Figure 5: Lifetime of heat pumps - exchange rate of heat pumps according to the age after installing

The evaluation of the sales figures and the lifetime curve for the years 2016 to 2018 results in the following figures for the field inventory of geothermal heat pumps in Germany.

Field inventory of geothermal heat pumps

year	geothermal heat pumps
2016	340,000
2017	362,000
2018	382,000

3.3.2 Average Coefficient of Performance (COP) and average Seasonal Performance Factor (SPF)

The Wärmepumpen-Testzentrum der Interstaatlichen Hochschule für Technik (WPZ BUCHS) measured the COP of heat pumps according to the EN 255 and EN 14511 during the last years. If one compares the measurements over time, it can be seen that there is a correlation of the COP and the year of audit, which can be described by a linear function (Fig. 6).

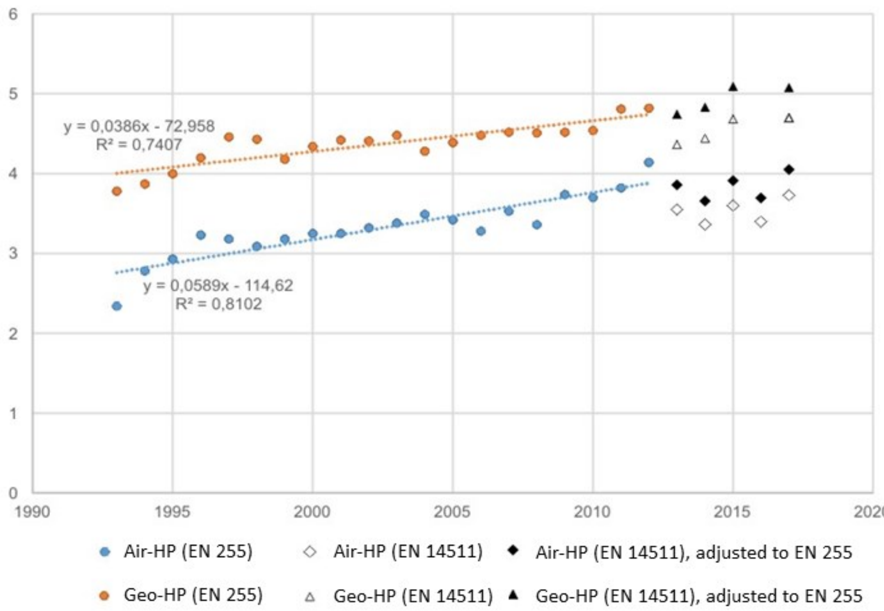

Figure 6: Progression of COP EN 255 [own diagram based on Eschmann, WPZ Buchs, 2012 & 2009-2013 and WPZ Buchs, 2017a&b]

The improved COP of the systems - as standardized laboratory values - are also reflected in the actual operation of the installed systems. The Fraunhofer ISE (ISE, 2010, 2011 & 2014) published a couple of studies that evaluated the seasonal performance factor (SPF/JAZ) of different heat pump installations under real-life conditions. Comparing with the COP of a specific year, the identified SPF reaches about 77% (air) and 80% (ground) of the COP. Therefore, the SPF can also be described as a function depending on the year of installation (Fig. 7). Ground source heat pumps that were installed in 2018 have an average SPF of 3.99.

3.3.3 Average Full Load Hours per Year

The average full load hours per year of a heating system is a factor during the planning process, which depends on building physics, the climate of the location, the kind of utilization, the heat demand and the question if the heat pump is used for heating and/or hot water. Normally, the average full load hours should not depend on the heat generator. Values for full-usage hours empirically collected are not available, but there are a couple of references which specify the average full load hours per year (BWP, 2011 & 2013; European Commission, 2013; SIA, 2010; VDI, 1993, 2001 & 2015) with a spread from 1,800 h/a up to 2,400 h/a. By consideration of all presumptions it seems to make sense to calculate with a value of 2,050 h/a, but it should be noted that this value is quiet vague. A deviation of the hours by x-% (e.g. 2,200 h instead of 2,050 h which corresponds to + 7.3%) leads directly to higher or lower numbers for the following calculation of the energy quantities.

3.3.4 Calculation of Capacity, Usable Heat and Renewable Energy

The renewable heat that is provided by geothermal heat pumps in Germany is calculated in the following way.

The usable heat of all installed heat pumps is the product of the number of installed heat pumps multiplied by the average capacity and multiplied by the full load hours.

$$Q_{usable} = H_{HP} \cdot P_{rated}$$

where Q_{usable} is the estimated total usable heat delivered by heat pumps [GWh], H_{HP} are the equivalent full-load hours of operation [h] and P_{rated} is the capacity of heat pumps installed [GW]

$$P_{rated} = n_{hp} \cdot P_{avg}$$

where n_{hp} is the number of installed heat pumps and P_{avg} is the average capacity of all heat pumps [kW]

The renewable energy (E_{RES}, pure geothermal contribution) is the total useable heat minus the operating energy for the heat pump (electric energy) according to the average SPF.

$$E_{RES} = Q_{usable} \cdot (1 - \frac{1}{SPF})$$

Table 4a shows the calculated values for the total installed capacity of all heat pumps P_{rated}, the total usable heat Q_{usable} and the pure geothermal contribution E_{RES} for the years 2016 to 2018 (see also Tab. 4b). The respective field inventory of heat pumps in age classes was calculated by individual installation year and then summed up.

The input variables “number of heat pumps”, “SPF” and “average capacity” differ between brine/water and water/water systems and depend on age. The “full load hours”, on the other hand, are independent of system type and age. As mentioned earlier, the average capacity of newly installed heat pumps in 2018 is 10 kW for brine/water and approximately 16 kW for water/water systems on average. For the field inventory of all installed and running heat pumps in 2018, the average capacity is around 11.5 kW.

Table 4a: Installed capacity, usable heat and renewable energy provided by geothermal heat pumps

	2016	**2017**	**2018**
P_{rated} [MW]	3,880	4,085	4,400
Q_{usable} [GWh]	7,950	8,375	9,025
E_{RES} [GWh]	5,800	6,150	6,600

Table 4b: Geothermal (ground source) heat pumps as of 31 December 2018

Locality	Ground or Water Temp. (°C)[1)]	Typical Heat Pump Rating or Capacity (kW)	Number of Units	Type[2)]	COP	Heating Equivalent Full Load Hr/Year	Thermal Energy Used[3)] (TJ/yr)	Cooling Energy (TJ/yr)
Germany	8 - 12	11.5 kW (average)	382,000	V, H, W, O			23,760	
TOTAL			**382,000**				**23,760**	

[1)] Average ground temperature for ground-coupled units or average well water or lake water temperature for water source heat pumps, [2)] V = vertical ground coupled, H = horizontal ground coupled, W = water source (well or lake water), O = others (e.g. energy piles), [3)] geothermal share only

As described above, the data and calculations are mainly based on the annual sales figures collected and published by German Heat Pump Association. Individual federal states in Germany pursue different approaches to collect a more comprehensive database. One example is presented in the next paragraph.

3.3.5 Data Collection on Shallow Geothermal Energy Utilization in Lower Saxony

Rather than depending on market sales of the heat pump producing industry, Lower Saxony, a federal state in Northwest Germany, is developing a database with the constructed geothermal projects.

According to German law (mining law and water law) every drilling irrespective of its purpose has to be announced. Lower Saxony developed an online drilling-notification many years ago for the notification under mining law. The notifications required under water law were made in an analog way at each water authority (53 in total in Lower Saxony). Since almost 100% of the drillings are registered with this online application, the State Authority For Mining, Energy and Geology decided in 2012 to expand it to registering geothermal projects according to water law. Thus, the notification under mining law and water law were combined in one online tool for geothermal projects.

Up to now, data from 7,000 of the known 15,000 installations in Lower Saxony are stored in this database. So now, not only the data of the drilling itself like location, depth and drilling method is collected but also data about the geothermal project that are relevant for the license under water law. This includes the following data:

- Type of geothermal system (borehole heat exchanger, horizontal heat exchanger, open well systems, exploration well, thermally activated foundation pile)
- Depth of project
- Planned beginning
- Total number (e.g. total number of borehole heat exchangers)
- Heat output of the installation (output of the heat pump)
- Cooling output (in case of cooling)
- Seasonal performance factor
- Full load hours
- Further information on the geothermal system, e.g. borehole heat exchanger:
  - Total meters of borehole heat exchangers
  - Type of borehole heat exchanger (e.g. U-type)
  - Type of heat carrier fluid
  - Type of grouting material

These data allow the state authority and the water authorities easy access to statistics for the federal state and its administrative districts. Figure 7 shows an example of one of the different statistics available from the database for a larger administrative district in Lower Saxony. Here, the new geothermal installations broken down to the type of system are plotted for each year. In this case, the local authority can see a successive growth of the market, that borehole heat exchangers have a dominant market share and open well systems are rarely used.

It is not only possible to see the development of the market for shallow geothermal systems in Lower Saxony but also to detect trends in installation configuration. Furthermore, it allows an overview on used materials (heat carrier fluid and grouting material) and the possibility to select installations with specific properties.

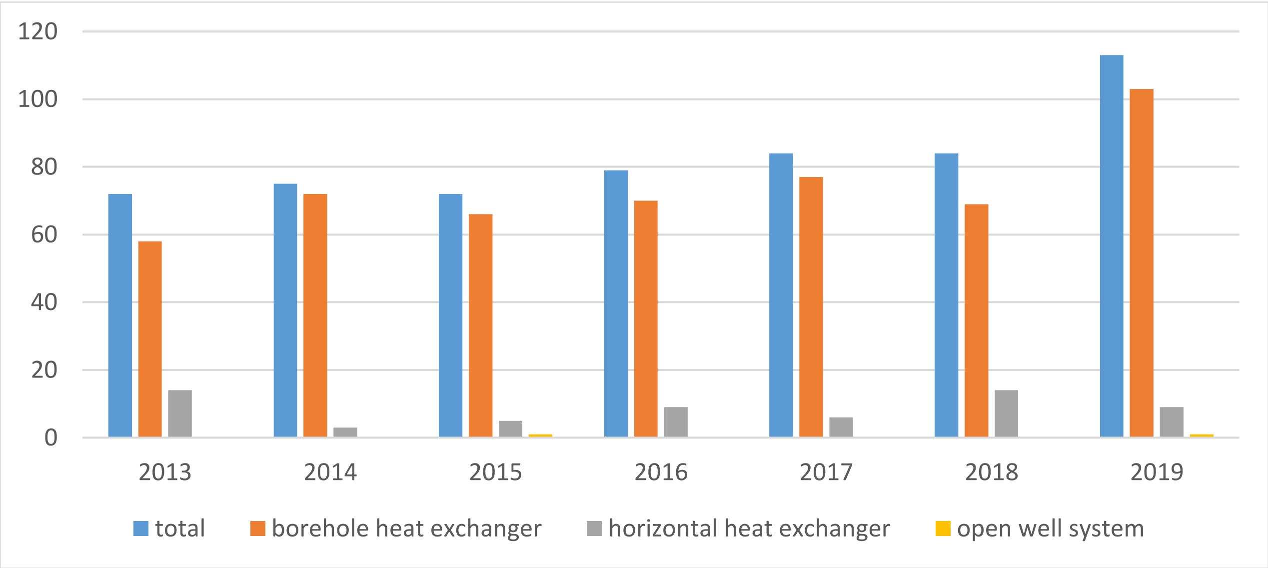

Figure 7: Number of new geothermal installations broken down to the type of heat pump system for a larger administrative district in Lower Saxony for the last seven years.

4. GOVERNMENTAL SUPPORT

4.1 Energy Market and the Role of Geothermal

According to BMWi (2019a), the final energy consumption in Germany added up to 9,329 PJ in 2017. About 54% of the final energy consumption was required for district and space heating, hot water and process heat.

Most of this demand at present is supplied by fossil fuels. A significant proportion of this demand could be, in principle, supplied by geothermal heat. This would make a significant contribution to reducing the present CO_2 output of Germany.

According to the German Federal Environmental Agency (UBA, 2018) the total heat demand in Germany was 4,931 PJ in 2016 (Fig. 8). The three sectors industry, commerce and residential have a total heat demand of 2,973 PJ for heating and hot water of which the residential sector alone accounts for 2,009 PJ. Shallow to medium deep geothermal applications combined with heat pumps can provide heat on a relatively low temperature level suitable for (space) heating and/or hot water.

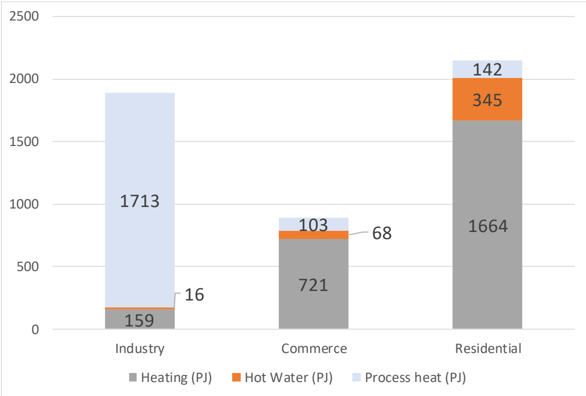

Figure 8: Heat demand by sectors 2016 (UBA, 2018)

In 2018, the installed geothermal heat pumps supplied 1.62% of the residential heat demand (1.18% renewable energy) or 1.09% of the total heat demand for heating and hot water (0.8% renewable) in Germany. Based on this, there is still huge potential to replace fossil fuels by geothermal energy, especially in the residential sector. Together with centralised installations, the geothermal sector in Germany provided a total of about 29,139 TJ of heat in 2018 (Tab. 5).

Table 5: Summary table of geothermal direct heat uses as of 31 December 2018

Use	Installed Capacity (MWt)	Annual Energy Use[1)] (TJ/yr = 10^{12} J/yr)	Capacity Factor[2)]
Individual Space Heating[3)]	3.34	35.21	0.33
District Heating[3)]	346.2	3,634.87	0.33
Air Conditioning (Cooling)			
Greenhouse Heating			
Fish Farming			
Animal Farming			
Agricultural Drying			
Industrial Process Heat			
Snow Melting			
Bathing and Swimming[4)]	56.8	1,708.56	0.95
Other Uses (specify)			
Subtotal	**406.3**	**5,378.6**	
Geothermal Heat Pumps	4,400	23,760	
TOTAL	**4,806.3**	**29,138.6**	

[1)] Geothermal share only; [2)] Capacity Factor = [Annual Energy Use (TJ/yr)/Capacity (MWt)] x 0.03171; [3)] Other than heat pumps; [4)] Includes balneology

The German government has an agenda for the transformation of the energy sector in Germany until 2050 to reach the ambitious national climate protection targets. After all Germany has set the target to reduce the greenhouse gas emissions by about 90%-100% within the next 30 years. Heat pumps shall be one of the key technologies to reach the targets, especially for the heat supply. However, there is already a gap between the current additional installed heat pumps per year and the aim of 5 to 6 million installed heat pumps in 2030. The Fraunhofer Institute IWES/IBP quantifies this gap: 3 to 4 million heat pumps will be lacking in 2030 (Fraunhofer IWES/IBP, 2017).

To fill the lack within in the next 15 years is not only a question of the rate of modernisation and the will of private owners to trust in heat pump technologies. Open issues are moreover the capacity and the knowledge of plumbers and drilling contractors to install the systems, the training and education structure, the development of energy costs, the progress of the modernisation of existing heating systems and not least the legal framework in Germany. A higher market penetration can be reached if the counterpart, fossil heating units, will be pushed more or less out of the market. The procedure could be a (partly) prohibition of fossil heating units or an additional fee for gas and oil to raise their market price.

A political debate is currently (in mid-2019) underway on the option of taxing CO_2. The primary aim is not to promote heat pumps, but to inhibit climate-damaging technologies. If a CO_2 tax would be introduced in Germany, it can be assumed that heat pumps will gain market share in the heating market compared to gas and oil heating systems.

Table 6 shows the number and total depth of wells drilled for geothermal utilisation. The numbers are estimated based on the data available in the Geothermal Information System GeotIS (GeotIS, 2019).

Table 6: Wells drilled for electrical, direct and combined use of geothermal resources from January 1, 2015 to December 31, 2019 (excluding heat pump wells)

Purpose	Wellhead Temperature	Number of Wells Drilled				Total Depth (km)
		Electric Power	Direct Use	Combined	Other (specify)	
Exploration[1)]	(all)	2				9.5
Production	>150° C			1		5.6
	150-100° C			1		3.8
	<100° C		5			16.4
Injection	(all)		4	2		24.5
Total		2	9	4		59.8

In Germany, there is no official data available on the allocation of professional personnel in the geothermal sector for the years 2015 to 2019. An estimation would be too ambitious.

4.1 Governmental Support

Germany has set ambitious national climate protection targets including the phase out of nuclear energy by 2022. The German Government aims for an energy supply based predominantly on renewables, meeting 80% of the electricity demand and 60% of the gross final energy consumption by 2050 (BMWi, 2014a).

Considering the large potential of geothermal energy and its valuable contribution to a renewable energy supply, the BMWi supports various related research projects. The funding comprises all aspects of geothermal technology, from planning and exploration to drilling and operation of plants, with the aim to reduce the costs of geothermal projects and to make them economically successful.

Apart from funding R&D projects (Tab. 7), the Federal Government created incentives for new projects by offering a feed-in tariff for geothermal electricity and the Renewable Energy Sources Act (EEG). The amendment of the EEG with improved conditions for geothermal energy has come into effect on 1st January 2012. The subsidy for geothermal electricity has been increased to 25 €-cents/kWh with additional 5 €-cents/kWh for the use of petrothermal (EGS) techniques. A revision of the EEG in summer 2014 abolished the petrothermal bonus, and deteriorated the economic boundaries for selling electricity.

Table 7: Total investments in geothermal in €

Period	Research & Development Incl.	Field Development Including Production	Utilization		Funding Type	
			Direct	Electrical	Private	Public
	Million €	Million US$	Million US$	Million US$	%	%
1995-1999						
2004	11.9					
2005-2009	81.1					
2010-2014	96.8					
2015-2018	55.3					

Source: BMWi (2014b & 2019b)

The Renewable Heat Act (EEWärmeG) of 2009, which came into force in an amended version in 2011, mainly aims at the installation of renewable heat sources in buildings. An obligation for use of renewable energy in new buildings is given in EEWärmeG; geothermal heat pumps are eligible if they meet the criteria, for example certain quality labels, a minimum coverage of 50% of the annual heat load by the heat pump, and a minimum seasonal performance factor (SPF). The EEWärmeG, and a similar act on the state level in Baden-Württemberg, did not yet prove to be useful for geothermal heat pumps; in the absence of reliable statistics detailing the causes for investment, the main share of renewable energy installations triggered by these obligations seems to be in solar thermal systems for domestic hot water.

Since a couple of years, the German government provides a grant for new heating technologies by the market stimulation program (MAP). The rules of the MAP changed a couple of times in the past (amount of the grant, type of technologies, grant for new and/or existing buildings). Since 2015, very good conditions for the installation of geothermal heat pumps were established. The minimum grant for geothermal heat pumps was raised to €4,000 and can be over €7,000. The better conditions led to an increase in the number of subsidised heat pump units: from about 8,500 in 2016 to already about 11,700 supported heat pump installation until 31th October 2017 (BAFA, 2016 & 2017).

In addition, there are some corresponding programmes in the federal states. For example, North-Rhine-Westphalia includes geothermal heat exchangers and geothermal wells for heat pumps in the existing progres.nrw programme. Heat exchangers will be supported with 5 € per borehole meter for new buildings up to 10 €/m for existing buildings, and wells get subsidised by 1 € per liter flow rate per hour.

5. OUTLOOK

As already mentioned earlier, about 54% of the final energy consumption in Germany is required for district and space heating, hot water, and process heat (Arbeitsgemeinschaft Energiebilanzen, 2018). However, the renewable energy share in heat grew unsteadily and even dropped from 2012 to 2018 to 13.9% (BWMi, 2019b).

This could be a chance for geothermal energy, which has an enormous potential for expansion along with low land requirements. The geothermal gradient can be used in all scales resulting in a whole variety of geothermal applications. In many areas of heat generation fossil fuels such as coal, oil and natural gas can be substituted by geothermal energy. One example is the city of Munich, which aims to provide 100% of district heating from renewable energies by 2040 as the first German metropole.

Deep geothermal energy plays a key role in this visionary plan due to the favourable geological subsurface conditions. The expansion of the geothermal heat grids enables a faster implementation of the heat transition than the energetic renovation of existing buildings (Moeck & Kuckelkorn, 2015).

Also for shallow and medium-deep geothermal resources, there is still a large growth potential through the utilisation of ground source heat pumps, especially for new buildings. Additionally, many outdated heaters must be replaced in the private sector in the coming years. One solution are ground source heat pumps. With already more than 380,000 installed systems in Germany, GSHP are a widespread, successful and affordable technology (Born et al., 2017).

Therefore, heat pumps can be used for a reliable and predictable heat transition due to the market-ready technology not only for shallow but also larger depth. The strength of geothermal energy is its scalability and the wide range of applicable technologies depending on depth and user demand.

Although prices for oil and gas are low at the moment, it is necessary to invest in the energy of the future and increase the development of geothermal energy, since this technology, in contrast to other renewables, is predestined to secure the heat supply of Germany.

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