Geothermal Resources for Electric Power Production in Germany

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Abstract

Organic Rankine and Kalina cycle technique allow efficient electric power production at temperatures as low as 100 °C and makes geothermal power production attractive even for countries like Germany lacking high enthalpy-resources at shallow depth. In a study performed in 2002 the geothermal resources for geothermal power production in Germany were estimated. Three types of reservoirs were considered: hot water aquifers, faults and crystalline rocks with temperatures above 100 °C and at depths down to 7000 m. Assuming realistic values for the recovery factor and the efficiency the accessible electric energy was calculated. The electrical energy was estimated to 10 EJ (1 EJ = 10^{18} J) for the hot water aquifers, to 45 EJ for deep reaching faults, and to 1100 EJ for crystalline rock. This corresponds to an annual power consumption of 2 EJ for Germany. These huge resources justify further F&E developments especially for the exploitation of heat from faults and crystalline rocks.

Keywords

Geothermal resources, geothermal energy, Hot-Dry-Rock, geothermal power production, Hot-Water-Aquifers

Introduction

Modern conversion techniques, ORC- and Kalina-Cycle enable electric power production at temperatures down to 100 °C and makes geothermal power production a potential option even for countries like Germany lacking high enthalpy resources at shallow depth. Its high availability (independent of the season and daytime) and its high potential for reducing the emission of greenhouse gases attracted members of the German Parliament and lead them to initiate a study on the potential for geothermal power production in Germany. The "Office of Technology Assessment at the German Parliament (TAB)" coordinated this study and subcontracted three expert teams for sub-studies on the geothermal potential, the exploitation and conversion techniques and on the implementation of geothermal power in the existing power market in Germany. These sub-studies were finished in autumn 2002. A synthesis of these studies was written by the TAB and will be presented to the German Parliament in the first half of 2003. The present article summarises the results of the first sub-study [1] on the geothermal power potential in Germany written by the Geocentre Hanover. It is the first attempt on this topic and is complementing the German contribution to the Atlas of Geothermal Resources in Europe [2], [3], whose main emphasis is related to the direct use of geothermal energy.

Geothermal resources: definition and assessment

The base exploitation scheme for this study is a doublet system consisting of a production borehole and an re-injection borehole both accessing the same reservoir at a distance great enough to sustain geothermal power production for a time period of at least 25 years. The most critical parameter for such exploitation scheme besides temperature is the hydraulic conductivity of the reservoir (the permeability of the rock or the transmissivity of the structure). In our study only those reservoirs were defined as resources whose hydraulic conductivity is sufficient to maintain a production and re-injection flow rate of water of at least 50 m^3/h. This of course is for the present energy prizes in most cases too low for economical power production. The parameter values chosen to define a reservoir as a resource are summarised in Table 1.

Maximal Depth	Z_{max}	7 km
Minimal production temperature	T_{min}	100 °C
Injection temperature (power)	T_{IN}	70 °C
Injection temperature (CPH)	T_{IN}	50 °C
Injection temperature (CPH H)	T_{IN}	30 °C
Minimal flow rate	Q_{min}	$50\ m^3/h = 14 \cdot 10^{-3}\ m^3/s$
Maximal pressure difference	Δp_{max}	$80\ bar = 8 \cdot 10^6\ Pa$
Minimal transmissibility	T_{min}	$2 \cdot 10^{-12}\ m^3 = 2\ D\ m$

Table 1: Base values for the assessment of the geothermal resources

Three types of reservoirs were considered as being capable to meet the requirements for geothermal power production: hot-water aquifers, deep reaching faults, and crystalline rocks. Though geothermal energy is classified as a renewable energy it has to be treated as a limited resource like conventional energy sources since for technical applications its exploitation is locally not balanced by the heat production and by the natural heat flow. The time period to restore the heat content in a certain volume is generally much longer than the time period of its exploitation. The method of choice to quantify the geothermal resources is therefore the volume method as described in [4]. This method uses the following equations:

$$H_0 = c_R \cdot \rho_R \cdot V \cdot (T_R - T_0) \qquad (1)$$

$$H_1 = R \cdot H_0 \qquad (2)$$

$$H_{el} = \eta \cdot H_1 \qquad (3)$$

H_0 : Heat in place [J]
H_1 : Accessible heat [J]
H_{el} : Electric energy [J]
c_R : specific heat capacity of the rock [J/kg]
ρ_R : Rock density [kg/m^3]
V : Rock volume [m^3]
T_R: Rock temperature [°C]
T_0: Temperature at the surface [°C], (mean annual temperature)
R : Recovery factor [1]
η : Efficiency [1]

The recovery factor R defines what fraction of the heat in place can be exploited if a certain exploitation scheme (doublet-system in our case) is used. The values of the recovery factor used in our study are listed in Table 2. For the Hot Water Aquifers these values are based on empirical data given by [5].

	Hot water aquifer			Faults, Crystalline rock			
	R			R			η
Temp.-class [°C]	Power	CHP	CHP-H	Power	CHP	CHP-H	
100-130	14	20	27	2,4	2,9	3,2	10,3
130-160	18	23	28	4,0	4,9	5,3	11,7
160-190	21	25	29	4,6	5,5	6,4	12,6
190-220				5,0	5,8	6,5	13,1
220-250				5,3	6,0	6,6	13,5

Table 2: Recovery factors R and efficiencies η used in this study. CHP: Coupled Heat and Power Production, CHP-W: Coupled Heat and Power Production with heat pump

The applicability of the volume method for faults is not obvious since in many cases faults are better approximated by a plane rather than by a volume. Our study followed the method developed by [6]. This method treats faults as planes. When fluid is circulated through the faults heat is supplied from the rock volume on both sides of the faults. The thickness of the volume that can be exploited in this way is determined by the thermal diffusivity of the rock and by the time period of exploitation. For a thermal diffusivity of $\kappa = 10^{-6}$ m^2/s and an exploitation time of 100 years this thickness is 170 m on both sides of the fault. The heat contained in this volume is attributed to the fault (heat in place of the fault). The recovery factor listed in Table 2 refers to this heat content and was determined for an actual exploitation time period of 25 a by combining theoretical values calculated by [6] and empirical values given by [5]. The same values were applied for the recovery factor of the crystalline rock since we assumed that vertical parallel striking hydraulic fractures are created in the rock mass at distances of 340 m for exploitation. This scheme guarantees no thermal interaction between fractures (or Hot-Dry-Rock Systems) as long as they are exploited within a time period of 100 years.

Another limiting factor is the electric efficiency η. Due to the relatively low subsurface temperatures in Germany the efficiency is low even for the ORC or Kalina-Cycle process. The values listed in Table 2 were taken from [7]. These are gross values, which do not account for parasitic power consumption, e.g. pumping power. Net values for the efficiency are not easy to obtain since they depend on many conditions but they can for unfavourable conditions (temperatures near 100 °C and moderate hydraulic conductivity of the reservoir) be substantially lower than the gross values.

Subsurface temperatures in Germany

The GGA Institute maintains the most comprehensive data bank of the subsurface temperatures of Germany containing data from more than 10,000 boreholes. These data are not evenly distributed over the total area but are concentrated in regions with oil- or gas resources, i.e. the Northern German Basin, the Upper Rhine Valley, and the Southern German Molasse Basin. These are also the regions with hot water aquifers suitable for geothermal power production. For this reason these resources could be determined with regional details concerning temperature. The same applies for the crystalline rock (volcanic rocks of the Rotliegend) in the Northern German Basin. For most parts of Germany temperature data from greater depths are rare. Nevertheless the bulk of data indicates that the geothermal gradient at greater depths is close to normal (about 30 °C) over large parts of Germany and is enhanced only in the Upper Rhinegraben on a regional scale and at some anomalies on a local scale. The resources of the crystalline rock and of the faults were therefore determined by assuming a normal temperature gradient. Only for the Upper Rhine Graben higher temperatures were assumed.

Resources

Hot-Water-Aquifers

The most important Hot-Water-Aquifers are the Rotliegend-sandstone in the Northern German Basin [1], the Bunter-sandstone and the Muschelkalk-limestone of the Upper Rhine Valley [3], and the karstic Jurassic limestone (Malm) of the Southern German Molasse Basin [8]. There are some other potential formations but their temperature or transmissivity are only locally sufficient for geothermal power production. They were therefore neglected in this study.

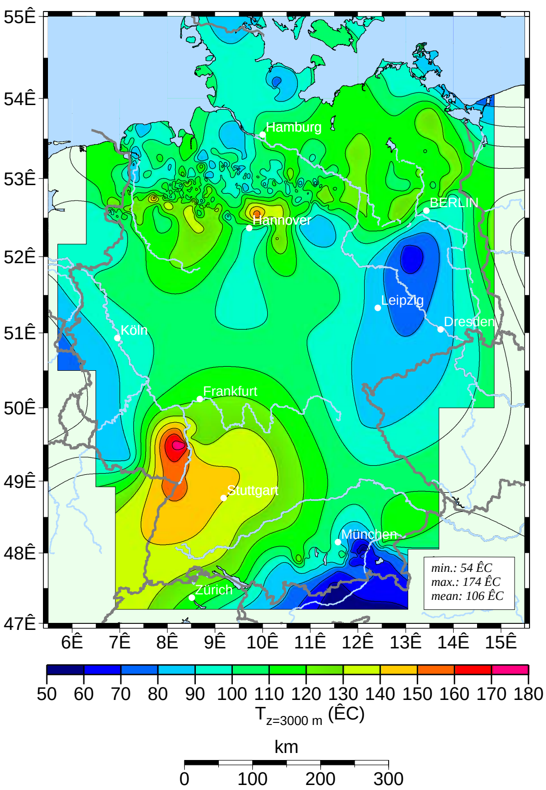

Figure 1: Isotherms at 3000 m depth

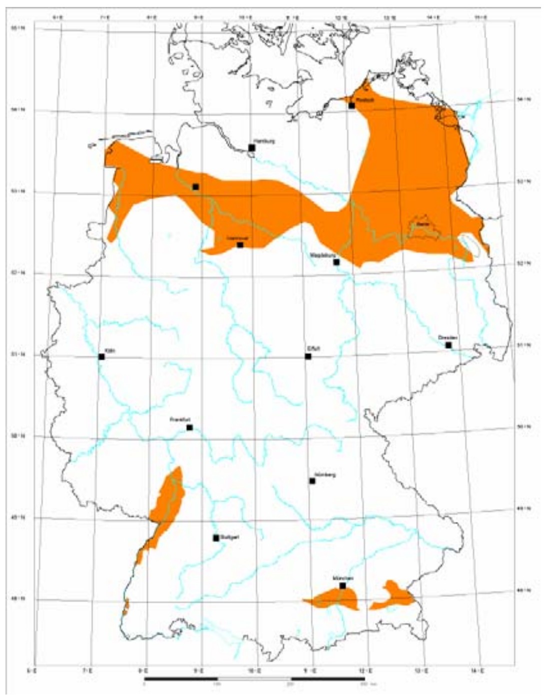

Figure 2: Hot-Water-Aquifers for power production

The resources of the Hot-Water-Aquifers are listed in Table 3. The total electric energy of these aquifers amounts to $9 \cdot 10^{18}$ J or $3 \cdot 10^{2}$ GWa. The hot water resources have their maximum in the temperature range 130 - 160°C except of the Malm, whose temperature does not exceed 130 °C. Resources in the temperature range 160 – 190 °C are rare and there are no resources with higher temperatures.

The electric energy of the hot water aquifers corresponds to about five times the annual power consumption in Germany. This number however has to be regarded as an upper limit, since our knowledge about the transmissivity of the aquifers is limited and it is likely that the transmissivity will be found to be insufficient on many locations. This uncertainty is a major obstacle for the exploitation of this resource. It is therefore recommended to evaluate all existing data for instance from the oil- and gas fields and to improve the interpretation technique for seismic surveys in order to get a better picture of the hydraulic properties of these aquifers on a regional scale.

At the present state of knowledge the Malm has the highest probability of success in terms of transmissivity but the temperature in this aquifer is limited to the range 100 – 130 °C. Demonstration projects (like Altheim in Austria, or Unterhaching near Munich) will show how efficient geothermal power production is at these low temperatures and what the costs are.

The Hot-Water-Aquifers of the Upper Rhine Valley are attractive mainly for their high temperatures at relatively shallow depths. The knowledge about their transmissivity however is limited and the few values available from hydraulic tests indicate that their transmissivity is generally lower than that of the Malm. Demonstration projects started in 2001 will provide more information about their suitability for geothermal power production.

The biggest resource is the Rotliegend-sandstone of the Northern German Basin. Data about their hydraulic properties are mainly from gas fields with their specific geological settings and are neither representative nor open to the public. It seems however that even for these favourable locations the transmissivity does in many cases not meet the requirements for geothermal power production. This and the great depths make it difficult to use this aquifer. A demonstration project north of Berlin will show whether conventional hydraulic fracturing or massive waterfrac tests can improve these conditions.

Faults

The distribution of deep reaching faults is shown in Fig. 1. This map is a synthesis of several regional maps [3], [9], [10], [11], and [12] and contains all known faults with a vertical depth of more than 7 km. Many of them are fault zones rather than discrete planes but as mentioned above they were approximated by discrete planes for estimating the resource. Areas with a high density of faults are the Upper Rhine valley and a wide belt striking from the north-west corner of Germany to Bohemia. The main strike direction of the faults is NW-SE but also NNE-SSW striking faults are common. For our study they were not classified regarding their type (normal, transform or thrust faults) or orientation with respect to the present stress field. There is of course great uncertainty to what extent they can be used for geothermal power production since little is known about their hydraulic properties especially at great depth. But they at least bear a better chance than the competent rock to find higher transmissivity. For estimating the resource we assumed vertical dip of the faults and a normal temperature gradient of 30 K/km even for regions like the Upper Rhine Graben where the temperature gradient is enhanced.

The length of the faults varies from some tens to several hundred kilometres and adds up to a total length of about 20,000 km. The total electric energy of the faults amounts to $45 \cdot 10^{18}$ J or 1400 GWa. This is about five times the resource of the hot water aquifers and about 23 times the annual power consumption in Germany. This shows that faults are an interesting target for geothermal power production. Their steep to vertical dip allows exploiting them at arbitrary depth and there seems to be a good chance to enhance their hydraulic conductivity by massive water injection if it is too low.

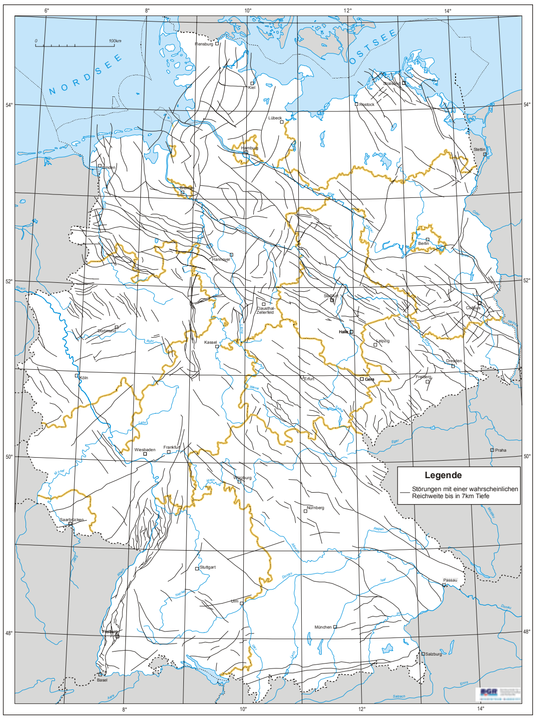

Figure 3: Major faults for geothermal power production

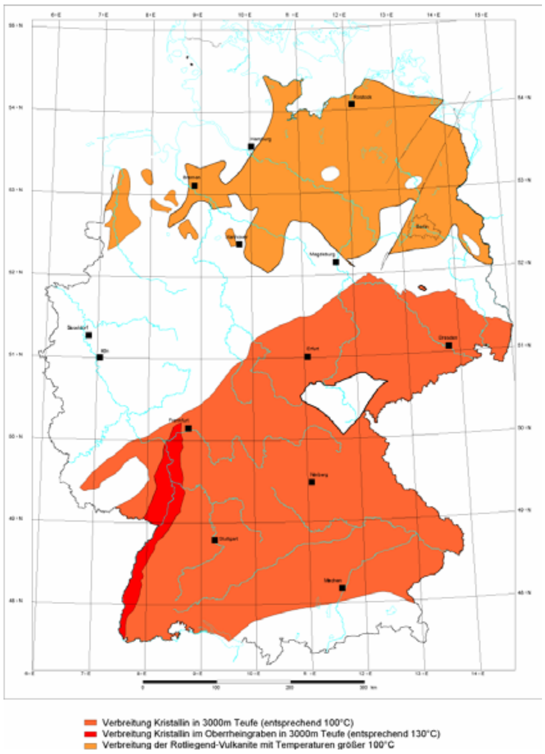

Figure 4: Regions with crystalline rock for geothermal power production

Crystalline rock

The exploitation of deep seated crystalline rock for geothermal power production has been the target of several international research projects during the past three decades [13]. The basic concept to exploit this tight type of rock is to connect two boreholes by creating large fracture systems and using them as an underground heat exchanger. The key technology is the waterfrac technique. It was shown that fracture systems with an extent of several square kilometres can be created in this way and that these fractures are kept open by a self propping effect. Presently this technique has been successfully applied only in granite or similar types of hard rock. We therefore restricted our resource study to regions of crystalline or highly metamorphic rock.

Fig. 3 shows the regional extent of these resources. There are two main resources: a big body of Permian volcanic rock in the Northern German Basin and the huge mass of the basement formed by granites and highly metamorphic rocks in the Middle and Southern German Crystalline Region [1]. The latter contains also the Upper Rhine Valley, a region with significantly enhanced temperature.

The determination of the resources was straight forward for the Middle and Southern German Crystalline Region since crystalline rock extents over the total depth range between 3 and 7 km. The determination of the resource in the Northern German Basin was more complicated due to the fact that the depth and the thickness of the Permian volcanic rock formation vary considerably.

The electric energy of the resource amounts to $1{,}100 \cdot 10^{18}$ J or 35,000 GWa. This is by far the biggest geothermal resource in Germany. It corresponds to about 600 times the annual electric power consumption in Germany.

The exploitation of this huge resource however requires further improvement of the Hot-Dry-Rock-Technology for different tectonic settings and does presently not reach economic standards.

Summary and conclusions

The total electric energy accessible from geothermal resources down to a depth of 7 km amounts to $1{,}200 \cdot 10^{18}$ J or 40,000 GWa. This huge resource corresponds to about 600 times the annual power consumption in Germany. The size, its high availability and its potential for reducing the CO_2 emission makes this resource a significant option for future energy supply and justifies further R&D-efforts.

	Electric energy [J]	Heat [J] CHP	Heat [J] CHP-H
Crystalline Rock	1,1 E+21	1,6 E+21	2,8 E+21
Faults	4,5 E+19	6,5 E+19	1,2 E+20
Hot Water Aquifers	9,4 E+18	2,3 E+19	5,0 E+19
Total [J]	**1,2 E+21**	**1,7 E+21**	**3,0 E+21**
Total [GWa]	**37,000**	**53,000**	**95,000**

Table 3: Geothermal Resources for electric power production and additional heat for Coupled Heat and Power Production with (CHP-W) and without (CHP) heat pumps.

The hot-water-aquifers are the smallest resource and are regionally limited but the exploitation technique is state of the art. R&D efforts should be directed toward reducing the economical risk resulting from our limited knowledge about temperature and hydraulic properties. They should include:

- Collecting and mapping of temperature and hydraulic data for these aquifers
- Improvement of exploration techniques for quantifying depth, thickness and hydraulic properties of the aquifers
- Improvement and testing of stimulation techniques for enhancing the productivity of geothermal boreholes.

Deep reaching faults are a very interesting resource for their wide distribution over large parts of Germany and for the fact that the depth for accessing the resource and consequently the temperature can be technically controlled within certain limits by using directional drilling. It seems also likely that the transmissibility of faults can be enhanced by massive water injections.

- R&D efforts should concentrate on more detailed mapping of faults, collecting hydraulic test data and on in-situ testing including massive waterfrac tests.

Crystalline rocks are by far the biggest resource.

- Research and demonstration projects are required for different tectonic settings.

Acknowledgements

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