Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Assessment of Geothermal Heat Provision from Deep Sedimentary Aquifers in Berlin/Germany: A Case Study

Oliver Kastner, Judith Sippel, Günter Zimmermann, Ernst Huenges

GFZ German Research Centre for Geosciences, Telegrafenberg, 1473 Potsdam, Germany

oliver.kastner@gfz-potsdam.de, judith.sippel@gfz-potsdam.de, guenter.zimmermann@gfz-potsdam.de, ernst.huenges@gfz-potsdam.de

Keywords: Hydrothermal plant, Northeast German Basin, well doublet, thermodynamics, urban heat supply

ABSTRACT

Regions of active volcanism offer high-enthalpic production rates at comparably low development costs, but most of the developed and highly energy-consuming countries do not possess such geothermal resources. Even here, the crust's heat potential is enormous and may be mined for direct heating or energy conversion purposes, but the potential is largely undeveloped for different reasons: Limited geological data induce development risks, technological challenges, high investment and limited public reception. This situation holds true for the low-enthalpic hydrothermal heat reservoirs of the Northeastern German Basin, and specifically for the city of Berlin, capital of Germany. This contribution aims at illustrating the thermal power of hydrothermal heat plants at urban scale for the Berlin region. For this purpose, we selected a specific plant design and evaluated the heat production capacity of Post-Permian reservoir units (Middle Buntsandstein). This was based on a regional-scale structural model and statistically derived geohydraulic model parameter of the Northeast German basin; see Kastner et al. (2014) for the details of the underlaying model. In this contribution, we discuss the model results for the campus of the Technical University of Berlin, which may serve as a showcase.

1. INTRODUCTION

The primary energy consumption of the German economy amounts to 13,908 peta joule in 2013, cf. AG Energiebilanzen e.V. (2014). This number is regarding the total energy supply from any imported, home mined and renewable sources, excluding exports and bunkering, but prior to any conversion processes take place. The primary energy consumption has slightly increased 2012-2013 by 2.5%, while the total electric energy production remained stagnant during this time. A closer examination traces the increase of the primary energy back to enhanced needs for space heating during the particularly cold winter season of 2013. Heating in Germany is almost entirely based on fossil fuels, primarily natural gas and mineral oil. The cold winter in 2013 induced increased shares, by 2.2% for mineral oil and by 6.4% for natural gas. As a result the carbon emissions kept stagnant at a high level in 2013, despite a significant share of renewable electric power in Germany, thus thwarting the overall governance goal of carbon emission reduction. Therefore, to meet this goal the heat supply market has to develop a significant share from renewable resources in the future. Geothermal systems have the potential to contribute in principle, however, this potential is largely undeveloped for different reasons: Limited geological data inducing development risks, technological challenges, high investment costs and limited public reception. This situation is true especially for densely populated urban regions, comprising high demand and complex, heterogeneous supply structures. The city of Berlin/Germany may serve as a representative example of this.

An enormous potential (heat in place) of the deep sedimentary aquifers in Berlin's underground has been demonstrated (Kastner et al. (2013), Sippel et al. (2013)). Geologically, Berlin is situated in the Northeast German Basin, Fig. 1. The thermal gradient in this region is moderate, but promising hydrothermal reservoirs are expected in porous rock formations predicted at elevated depths between 1,000 and 5,000 meters. Typical reservoir formations in the region consist of sandstone units of variable thicknesses. The pore space of these units contains aqueous fluids characterized by depth-related temperature and salinity; this water body may be developed to utilize the heat potential by hydrothermal plant systems: The fluid is pumped to the surface through production wells and after heat extraction pumped back through corresponding injection wells to stabilize the formation pressure.

A preliminary assessment of the thermal capacities of such heat plants in Berlin are investigated in the follow-up study Kastner et al. (2014) (submitted). In the framework of this extended conference paper we refer to this work. The model relies on an existing structural model of the Berlin/Brandenburg region (Fig. 1a), which resolves the relevant reservoir formations at major unit scale. The required transport parameters are derived statistically from available field data of the Northeast German Basin within specific intervals of confidence. The resulting geological model, therefore, represents the present state of public knowledge for this region. The hydrothermal heat plant model was elaborated under the fundamental assumption that this database is sufficiently accurate to address the main tendencies on average. Under the constraint imposed by the geological uncertainties, an idealized heat plant design is considered, which deliberately ignores a range of inferior details: temperature and pressure losses along the piping, impact of the fluid chemistry, technical restrictions resulting from pump efficiencies, surface heat networks and buildings, as well as possible improvements due to different well design, development strategies and plant operations. To rationalize this complexity, we select a specific scenario and evaluate the geological model. This scenario is characterized by the assumption of a specific plant design and re-injection temperature, standard confined aquifer conditions and idealized fluid properties along the pipe system. The operation point of the heat plant is selected so as to prevail absorbing conditions in the injection well. This model is employed to assess the heating powers of virtual doublet systems fed from the Middle Buntsandstein. In this contribution, we specify the results for a selected site in Berlin, the location of the campus of the Technical University of Berlin. The campus is located at the city's decumanus in the western part of the city (N52.511332°, E13.326912°), indicated by the white triangle "TUB" in the contour map of Fig. 2B.

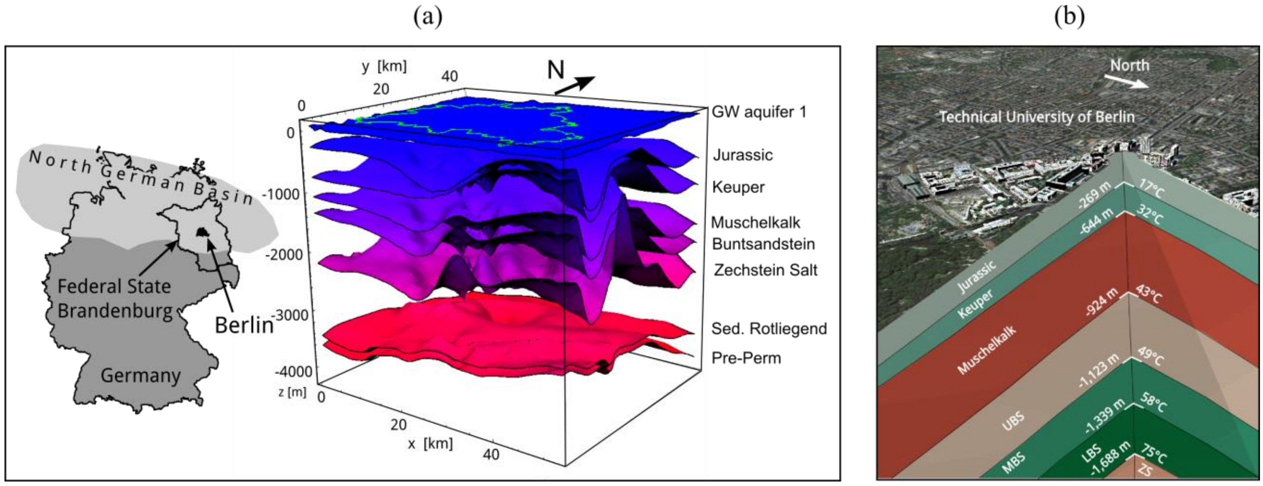

Figure 1: The city of Berlin is the capital of Germany and located in east Germany (a), exhibiting the sedimentary geology of the Northeast German Basin. The basin comprises a landform influenced by mobilized Zechstein Salt forming characteristic diapir structures. The Campus of the technical University of Berlin (b) in a true scale perspective representation combining surface and subsurface entities. Abbreviations: Upper (UBS) / Middle (MBS) / Lower (LBS) Buntsandstein, Zechstein Salt (ZS). Surface tile: Google Earth®, Berlin Senate Department for Urban Development and Environment.

2. GEOLOGICAL MODEL

The study is based on a structural model of the larger Brandenburg area provided by Scheck-Wenderoth and coworkers (Noack et al. (2010), Cacace et al. (2010), Jaroch (2006)). Out of this area, the Berlin region, located in the center of the federal state Brandenburg / Germany, was cropped and the resulting model was calibrated against additional well-bore data available, see Sippel et al. 2013 for a detailed description. The geographical location of the state Brandenburg and Berlin in Germany are shown in Fig. 1a. The model area covers a rectangular region of 53 x 43.5 km2, located between Gauss-Krüger coordinates 4,571,450 m – 4,624,450 m (latitudinal) and 5,800,300 m – 5,843,800 m (longitudinal), 3-degree Gauss-Krüger zone 4 (DHDN4). The Berlin model resolves geothermal reservoirs at main formation scale, hence neglecting decent complexities, like faults or present inhomogeneities at the scale of their sub-units. The resulting structural model therefore is suited for the assessment of the principle average properties within uncertainties induced by missing knowledge of the geological fine structure.

Berlin is located in the Northeast German Basin where the geometries of Mesozoic sedimentary units are typically complex because of recurrent phases of mobilization of the underlying Permian Zechstein Salt (Scheck et al. (2003), Stackebrandt et al. (2010), Scheck-Wenderoth (2008)); Fig. 1a provides a perspective view of the structural model in Berlin. The adjacent unit above the Zechstein Salt, the Buntsandstein, has experienced an approximately uniform deformation, indicated by relatively constant present-day thicknesses, while geologically younger sediment units additionally show erosive and non-depositional thinning atop the characteristic Salt diapirs (Sippel et al. (2013)). The Middle Buntsandstein exhibits hydrothermal aquifers comprising sandstone sequences, which are separated by low-conductive sequences of clay, siltstone and anhydrite. The sandstones are variably permeable according to the local facies. The sandstone fraction of a unit's structural thickness may be used to characterize the hydrothermally effective thickness. This fraction may be estimated based on the basin-wide average values known from the hydrocarbon exploration campaigns during 1960-1990, see TGL 25234/11 and Franke (2011). The Middle Buntsandstein is sub-devided into four sub-formations, the Solling-, the Hardegsen-, the Detfurth and the Volpriehausen formations, which consist of alternating sequences of sandstone, siltstones, claystones and anhydrite at variable stages of rock diagenesis (Fuchs and Förster (2010) and Feldrappe et al. (2008)). Sedimentary units are inhomogeneous in general and consist of a porous rock skeleton and a pore fluid. Both solid and fluid are mixtures at variable composition on their own, but within the scope of this work, we consider these as homogeneous each. The pore volume, characterized by the porosity, is assumed saturated by the pore fluid. We further assume that the porosity, the permeability and the equations of state for the pore fluid may be approximated by universal functions of depth. In doing so, we distinguish between primary field variables, which are related to the depth in phenomenologically known manner, and state equations of these quantities. The primary variables are the porosity Φ, the fluid temperature T and the fluid salinity c. The state equations are the fluid density, the fluid pressure, the dynamic viscosity, the permeability and the specific heat capacity (Kastner et al. (2013), (2014)).

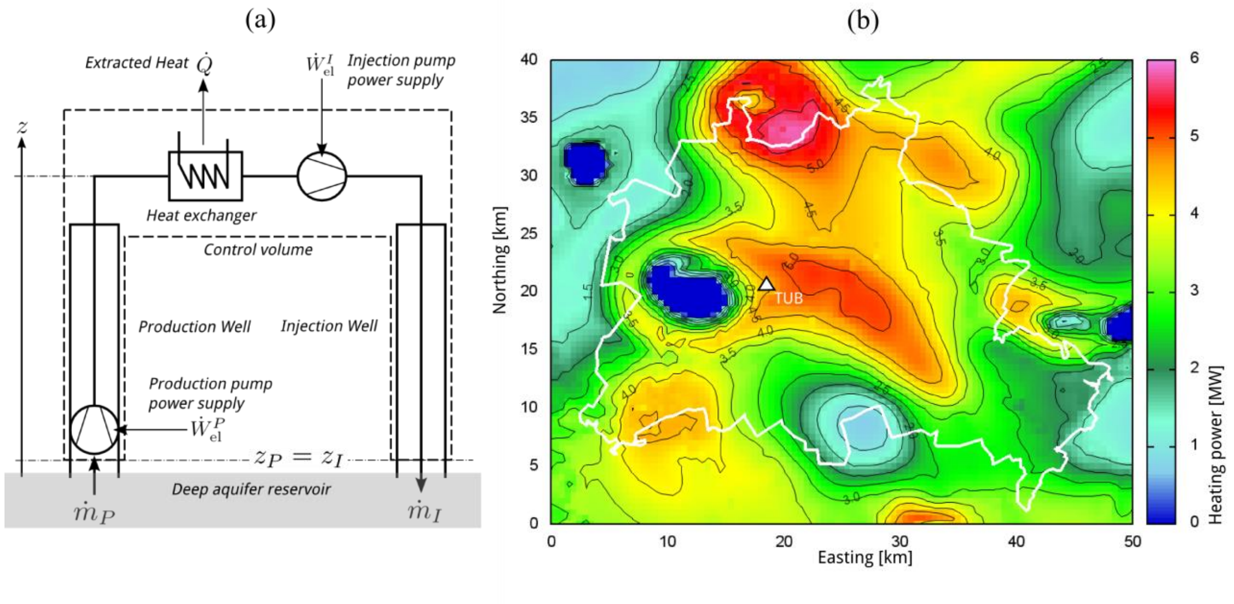

Figure 2: (a) Components of the hydrothermal model heat plant. (b) Modeled heating power of hydrothermal doublet systems mining Middle Buntsandstein aquifers in the Berlin region (Gauss-Krüger coordinates in km relative to 4,571.45 km easting, 5,800.3 km northing, German zone DHDN4. The border of Berlin is indicated by a white line. The campus of the Technical University of Berlin is marked by white triangle "TUB". The blue-coloured spots identify areas of reduced heat production. These are located at higher altitude level (atop of Zechstein salt diapirs), where the reservoir temperature approaches the assumed reinjection temperature of 45°C.

In the Northeast German Basin, the porosity is primarily a function of the burial depth owing to compaction. The deposition process of the sedimentary material during geological ages and the ongoing rock diagenesis also play a role. We rely on porosity distributions based on core data taken from wells in the Northern German Basin published by Wolfgramm et al. (2008) and use this data to fit a phenomenological depth relation following Athy (1930). The reservoir temperature is established by heat transport from the hot mantle to the surface under the influence of radio-genetic heat production in the crust and convective transport through mobile fluids. In the Northeast German Basin, a tangible influence of the Zechstein Salt distribution was identified (Stackebrandt et al. (2010), Limberg 2011, Cacace 2010, Scheck-Wenderoth 2013, Noack et al. 2012, 2013, Cacace et al. 2013, Kaiser et al. 2013). The employed temperature field originates on a 3D finite-element model, Sippel et al. (2013). The fluid salinity/depth relation in the Northeast German Basin is influenced by diffusive and convective mass transpor (Müller and Papendieck, 1975). Here the depth profile is fitted against borehole data after Hoth et al. (1997). The salinity of typical reservoir formations varies between 0.15 – 0.35 kg L-1 (Keuper – Sedimentary Rotliegend). The thermal equation of state of the pore fluid as function of the fluid pressure, temperature and salinity is represented by a tri-linear equation after Magri et al. (2005). The respective compressibility, the thermal expansion and the salinity sensitivity follow work by Gibson and Loeffler (1941) and Millero et al. (1969). The depth dependence then is calculated from the momentum balance (Kastner et al. (2013)). The dynamic viscosity is related to temperature, fluid mineralization and pressure, after Kestin et al. (1981). The permeability is related to porosity. We again refer to the work by Wolfgramm et al. (2008) for field data of the Northeast German Basin and relate these to theoretical work by Pape et al. (2000) for an analytical representation. The resulting porosity/permeability relation exhibits significant scatter, spanning several orders of magnitude. The specific heat capacity is related to temperature and fluid salinity, with the leading effect given by the salinity. We employ a constitutive equation by Knoebel and Chou (1968), reduced to the leading effect of the salinity.

3. HEAT PLANT MODEL

We consider the simple geothermal doublet design of Figure 2a. The model used always regards stationary conditions and assumes the pore fluid is incompressible. Energy dissipation caused by the fluid viscosity and heat conduction as well as chemical effects (mineral segregation) are neglected. The hydrothermal plant delivers heat $\dot{Q}$ and consumes working power $\dot{W}$ to drive the production (index "P"') pump. We consider the situation of absorbing conditions in the injection well such that an injection pump is not required (see comment below). The energy balance reads

$$\dot{m}\, c_p (T^I - T^P) + \dot{m}\frac{1}{\varrho}(p^I - p^P) = \dot{Q} + \dot{W} \quad . \tag{1}$$

$\dot{m}$ denotes the production mass flux, c_p the heat capacity and $T^{I/P}$ and $p^{I/P}$ are the injection and production temperatures and pressures, respectively. The mechanical working of the production pump lifts the fluid over a distance of (S^P+$|Z_\infty|$) to the surface. S^P denotes the draw down of the hydraulic head relatively to the natural water table Z_∞ in the production well. To model this draw down we assume confined reservoir conditions and employ the Cooper/Jacobs relation,

$$S^P \approx \frac{\dot{m}}{\varrho}\frac{1}{2\pi\,\tau}\ln\frac{R}{2D} \quad . \tag{2}$$

This Equation (2) relates the draw down to the magnitude of the production mass flux, to the reservoir-properties through the transmissivity τ = M k ρ g / η, and to the doublet design through the well separation 2D and the borehole caliber R. The reservoir-properties are the hydraulic permeability k, the fluid density ρ and the dynamic viscosity η. The reservoir-dimension is expressed by the thickness of the pay zone M, which in turn may be proportionally related to the structural thickness in a phenomenological manner.

During heat production of the plant, re-injection of cooled fluid replaces hot pore fluid in the vicinity of the injection well, forming a growing body of colder water. This body is partly re-heated in contact with the rock skeleton (Blöcher et al. (2010)), but for unfaulted sedimentary aquifers, subsequent thermal recovery from the far field is expected at a time scale much longer than the lifetime of the plant (Kastner et al. (2013b)). This general comprehension seems to be confirmed for Sedimentary Rotliegend aquifers in the region by a thermal field experiment considering the recirculation of injected cold water (Henniges et al. 2012), as well as with an aquifer storage system in Berlin (Kranz et al. 2008) for shallower formations. The thermal recovery is slow for two reasons: restricted fluid convection and low heat conductivities. Modeling of free fluid convection due to thermal or chemical density gradients in the Northeast German Basin exhibits fluid velocities in the order of millimeters to centimeters per years (Cacace et al. (2010), Kaiser et al. (2011), (2013)), which is much slower than the fluid velocities induced by the well doublet (in the order of tens of meters per year). This consideration is confirmed by other modeling studies of comparable geological settings (Bjørlykke et al. (1988), Graven (1995), Raffensberger et al. (1999), Mottaghy et al. (2011), Schilling et al. (2013)). Larger natural convection fluxes, in contrast, are detected in situations of pronounced basal slopes (Fan et al. (2007)) or at elevated temperature gradients (Fournier (1990)), but such situations do not prevail in the Berlin region. The conductive heat recovery from the far field is restricted owing to limited thermal conductivities, which are on the order of 2-4 W m^{-1} K^{-1} (Norden and Förster 2006, Fuchs and Förster 2010). In the framework of this contribution we shall therefore assume absent heat recovery from far field during the plant's lifetime. We employ a geometrical argument for the selection of the well separation: Thermal break-through of the injected cold water body to the production well may be safely avoided if the separation of the well (2D) is larger than the radius of the injected cold water bubble during life time of the plant. This yields

$$2D = r_f = \sqrt{\frac{\dot{m}\,a}{\varrho \pi M \phi}} \quad . \tag{3}$$

Φ denotes the porosity, a the plant's life time and M the pay zone thickness.

To close the model it is required to assume the point of plant operation – the mass flux rate produced. Its magnitude depends on a range of design parameters many of which refer to the specific structure the plant is supplying to. These cannot be specified within the scope of this work. Instead, the following scenario is rationalized: the production flux is set such that the magnitude of the draw down equals the depth level of the natural hydraulic head, $S^P=|Z_\infty|$. This specific selection maximizes the production flux under the side condition of absorbing conditions in the injection well, which allows to spare the injection pump otherwise required. Under this assumption the point of operation is defined by

$$\dot{m} = \frac{2\,Z_\infty\,\varrho\pi\tau}{\ln\frac{2D}{R}} \quad . \tag{4}$$

The related mechanical working of the production pump is

$$\dot{W} = \dot{m}g|Z_\infty| - g\frac{\dot{m}^2}{\varrho}\frac{1}{2\pi\,\tau}\ln\frac{R}{2D} \quad . \tag{5}$$

The productivity index and the coefficient of plant operation read

$$\mathrm{PI} = \frac{2\,\pi\,\tau}{\varrho\,g}\,\frac{1}{\ln\frac{2D}{R}} \quad , \tag{6}$$

$$\mathrm{COP} = \frac{|\dot{Q}|}{\dot{W}} = \frac{c_p(T^P - T^I)}{g\left(|Z_\infty| - \frac{\dot{m}}{\varrho}\frac{1}{2\pi\,\tau}\ln\frac{R}{2D}\right)} \quad . \tag{7}$$

The latter represents the ration of the produced heat and the energetic effort to produce the fluid, which under the taken assumptions is represented by the production pump working only.

4. CASE STUDY

The hydrothermal model plant considered here produces heat and consumes mechanical power according to Eqs. (1) and (5). These energetic quantities are related to the geological parameters and the production mass flux. The thermal capacity is further influenced by the technical specifications of the heat supply network, which sets the temperature T^I of the re-injected fluid after heat extraction, thus imposing an important technical boundary condition. We optimistically assume in this study that T^I = 45°C is a feasible number, at least for space heating in structures that may exploit modern heating concepts like low-temperature panel heating or building core heating.

Fig. 2b shows the contour map for the resulting heating power of hydrothermal doublet systems fed from Middel Buntsandstein reservoirs in Berlin. The magnitudes are predicted up to 5.9 MW, with an area-wide mean value of 2.9 MW. These figures refer to the expectation values of the geological parameters and pay zone thicknesses. The spatial distribution of the heating power is dominated by the interplay of two competing tendencies of temperature and permeability. Temperature increases approximately linearly with depth while the permeability decreases exponentially. Temperature affects the caloric heat of the pore-fluid while permeability affects the production mass flux. Deeper aquifers therefore exhibit warmer fluid, but the hydraulic well productivity is reduced. The mass flux is dominated by the matrix permeability, which in turn is sensibly depending on depth within orders of magnitude. Another important parameter influencing the production mass flux is the pay zone thickness. For the Middle Buntsandstein, the model predicts production flux rates in the order of 50-150 kg s^{-1} in the hydrothermally favorable areas in Berlin, with an area-wide mean value of 56 kg s^{-1}. The productivity index, related inversely to the production flux, is predicted between 10-

50 L s^{-1} MPa^{-1} in favourable areas, at well separations between 650-1,500 m. Always under the taken assumption of $S^P=|Z_\infty|$, the production pump working is in the order of 100-300 KW on average, hence effecting a COP of 10-25.

These average values are certainly super-imposed by model tolerances. A closer examination of this is given for the selected location of the Technical University of Berlin, indicated by the white triangle "TUB" in Fig. 2b. The respective model parameters and results are given in Table 1. In this table, min/max ranges are indicated which reflect the impact of the expected geological parameter variances on the model results. These ranges are calculated by linear error regression, regarding the functions $Y_i = \{\dot{m}_{\mathrm{OP}}, \dot{Q}_{\mathrm{OP}}, \dot{W}_{\mathrm{OP}}, \mathrm{PI}_{\mathrm{OP}}, 2D_{\mathrm{OP}}\}$ about their respective average values as functions of the primary field variables X_j = {Φ(z), T(z), c(z)}:

$$Y_i|_{\min}^{\max} = Y_i|_{\mathrm{average}} + \sum_j \left(\frac{\partial Y_i}{\partial X_j}\right)_{\mathrm{average}} \left(X_j|_{\min}^{\max} - X_j|_{\mathrm{average}}\right) \quad . \qquad (8)$$

The average functions and confidence intervals are known as universal functions of the depth variable z, hence the variances ($X_j^{min/max} - X_{average}$) can be specified for a given reservoir horizon. As usual, linear error regressions may yield unphysical results where these variances or the related sensitivity of the target functions, $\frac{\partial Y_i}{\partial X_j}$, are large.

The structural model provides the depth coordinates of the top and bottom interfaces defining the nominal thickness of the unit at locally. The effective thickness of the pay zone is taken proportional to the nominal thickness due to the sandstone fraction known from borehole date of the Northeast German basin. The natural hydraulic head is $|Z_\infty|$=200 m and sets the draw down according to the assumption stated above. The influence of these two parameters, effective thickness and draw down, on the predicted heating power and production mass flux is separately illustrated in Fig. 3. The primary field variables T, Φ and c are evaluated at the nominal reservoir depth. For the TUB site, the average temperature of a reservoir in the Middle Buntsandstein is 54°C, the average porosity is 25% and the average salinity is 121 g L^{-1} . The fluid density increases with depth, dominated by the salinity. The average value is predicted at 1,075 kg m^{-3}. The depth profile of the dynamic viscosity is adjusted through temperature. It exhibits an average value of 6.462 10^{-4} Pa s. The specific heat of the pore fluid is also dominated by the salinity and exhibits a n average value of 3,643 J kg^{-1} K^{-1}.

The severest model uncertainties result from the hydraulic reservoir properties. The permeability/depth relation is influenced by drastic scatter of the underlying field data in the Northeast German Basin. The min/max ranges span several orders of magnitude! At the TUB site, the average permeability for the Middle Buntsandstein is predicted at 1.095 x 10^{-15} m^2, but it may well be three orders of magnitude smaller or on orders of magnitude larger. On average, the reservoir hydraulics therefore are promising, but there are significant uncertainties, with a comparably high productivity index of 66 L s^{-1} MPa^{-1}.

The TUB site is geologically situated at the slope of a salt-diapir-induced high-level landform, were the Buntsandstein is found at comparatively shallow depth. Therefore, it exhibits higher permeabilities but lower temperature locally. Accordingly, the expected reservoir hydraulics allow high flux rate. Since the heating power is proportional to the product of flux rate and temperature, a hydrothermal plant fed from the Middle Buntsandstein may well exhibit representative power, where a moderate temperature level is compensated by elevated production flux. On average, the heating power of such doublet system at the TUB site is predicted at 4.5 MW. Always under the assumption of $S^P=|Z_\infty|$ (absorbing injection well conditions), the predicted average production mass flux is 153 kg s^{-1} and the doublet design assumes a well separation of 1,625 m. Figure 3 reveals the influence of the estimated pay zone thickness on the predicted heating power and the predicted production mass flux for the Middle Buntsandstein at the TUB site. The diagram is parametric in the magnitude of the drawdown. The respective average/min/max values of Table 1 are indicated in this diagram. We see how the effective pay zone thickness and the draw down influence the plant capacity and productivity.

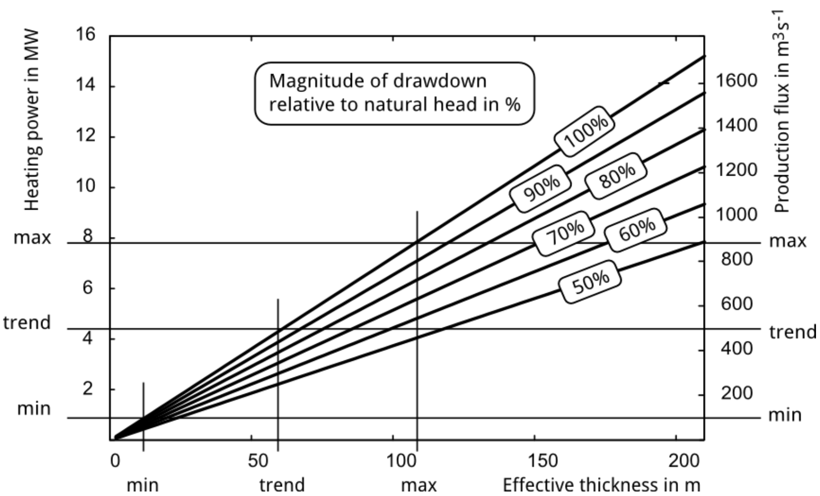

Figure 2: Influence of the payzone thickness of the Middle Buntsandstein reservoir on the predicted heating power and the production mass flux at the location TUB indicated in Fig. 2b

Nominal reservoir below surface / m		-1,272		average	$6.462\ 10^{-4}$
Nominal thickness / m		216	Dynamic fluid viscosity / Pa s	min	$5.462\ 10^{-4}$
				max	$9.062\ 10^{-4}$
	average	63		average	3,643
Effective Thckness / m	min	13	Specific fluid heat capacity / J kg^{-1} K^{-1}	min	3,406
	max	112		max	3,854
	average	54		average	1,625
Temperature / °C	min	43	Well separation subsurface / m	min	n.d.
	max	58		max	n.d.
	average	0.25		average	153.2
Porosity / -	min	0.16	Production massflux / kg s^{-1}	min	n.d.
	max	0.31		max	606.2
	average	$1.095\ 10^{-12}$		average	66
Permeability	min	$1.8\ 10^{-15}$	Productivity index / L s^{-1} MPa^{-1}	min	n.d.
	max	$5.771\ 10^{-11}$		max	263
	average	1,075		average	4.53
Fluid density / kg m^{-3}	min	1,043	Plant heating power / MW	min	n.d.
	max	1,124		max	20.92
	average	0.121		average	7.53
Fluid Salinity	min	0.064	COP	min	n.d.
	max	0.202		max	11.26

Table 1: Model parameters and results for a Middle Buntdsandstein reservoir located at the TU Berlin site, indicated by the white triangle "TUB" in the map of Fig 2b. Min/max ranges ate determined the linear error regression given in Eq. (7). Min ranges are not defined (n.d.) where the iear theory exceeds physically sound values.

5. DISCUSSION

This contribution references a model for preliminary assessment of hydrothermal heat plant capacities fed from deep, low-enthalpic aquifers in Berlin/Germany. The model relies on a structural model of the Brandenburg region, which resolves the relevant reservoir formations at major unit scale. Borehole data for the Berlin region are rare, therefore large parts of the required parameters have been fitted against field data available for the Northeast German Basin within specific intervals of confidence. This scenario is employed to assess the heating powers of virtual doublet systems fed from the Middle Buntsandstein. The model scenario yields realistic results for this reservoir unit, as compared with an existing hydrothermal plant in the Northeast German basin (WEMAG (1995), Schallenberg et al. (1999)). This plant is located 150 km north-west of Berlin. Heat is mined from a Triassic sandstone horizon at a burial depth of 2,300 m, comprising ca. 100 °C reservoir temperature. The plant has a doublet design with a well separation of 1,500 m. On average, the thermal heating power of this plant is 4.8 MW at a production flux of ca. 30 kg/s.

6. CONCLUSIONS

The development of hydrothermal energy supply systems in Berlin has to cope with the significant degree of uncertainty induced by the heterogeneous fine structure of the reservoirs. These uncertainties may well cause unproductive well conditions, thus setting up a prospecting risk that induces a substantial economical risk of well development. This risk has largely prevented hydrothermal plant technology in Berlin until now.

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