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Geothermal Adaptation of Abandoned Hydrocarbon Infrastructure - an Option for the Oil Industry to Extend Reservoir Utilization into the Area of Renewable Energy

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ABSTRACT

Hydrocarbon wells arc usually liquidated at the end of their life time but could be used instead for geothermal purposes, if potential heat consumers are at hand nearby. Common liquidation practice and retrofitting costs are rather contrary to the realization of such opportunities. In the future, by using inoperative but still not liquidated wells, chances may open up of extending the life time of some hydrocarbon fields by extracting renewable energy from existing wells. The feasibility of this approach, by using deep borehole heat exchanger technology, was tested for the area of the Vienna Basin, Austria, a major hydrocarbon source in Central Europe, on behalf of the Austrian oil company OMV. 270 wells were investigated. The results show that under local thermal and economic conditions it is difficult to achieve return of investment even on a long-term basis (30 yrs) for all but very few liquidated wells and for most wells currently still in service, too. This is especially true if a specialized company has to be contracted to operate the heat supply network. Given the prime cost for heal that network operators commonly accept (< 25 Euro/MWh) the thermal regime of the investigated area would have to be on the order of at least 160 mW/m^2 of terrestrial heat flow density, corresponding to geothermal gradients of 70 to 80°C/km. In Europe at least there are very few areas where such conditions prevail. For future work, a software tool (Geothermal Planning Tool) developed for the project and integrating the complete set of necessary technical and economic parameters and calculations, shall be applied to other regions where conditions arc more favorable.

1. INTRODUCTION

Deep borehole heat exchangers (DBHE) seem to offer an attractive way, in many places, to supply local housing or institutions (public buildings, enterprises, greenhouses, etc.) with heat for direct use. Commonly, heat will be of a rather low temperature, and houses newly built to the newest energy saving standards will gain the most from this sort of supply. So, on the one hand, the market for low-temperature heat continues to grow, as improved energy saving standards are being implemented, especially in the area of state-controlled urban development, but, on the other hand, drilling of new wells for the purpose is hardly economical. Therefore, attempts are being made to adapt existing boreholes, mostly drilled by the hydrocarbon industry, and associated supply lines, for geothermal utilization. The prospects of this approach are currently being tested in the Vienna Basin, Austria, one of the largest hydrocarbon fields in Central Europe (**Figure 1**). In cooperation with and financed by the Austrian hydrocarbon provider OMV, an interdisciplinary research group of experts is working on a project (Potential utilization of deep geothermal energy in the Vienna Basin, OMVTHERMAL far short) designed, on the one hand, to survey, evaluate and present the potential gain from geothermal resources and, on the other hand, to provide an easily manageable decision support tool for geothermal exploration on a broad scale, based on existing hydrocarbon drilling and reservoir as well as energy-related economic data. The whole complex of themes associated with this task is approached from geological and technical as well as engineering and economical points of view. Also, the foreseeable future is taken into account, both with regard to the future shut-down of wells and on the commercial side.

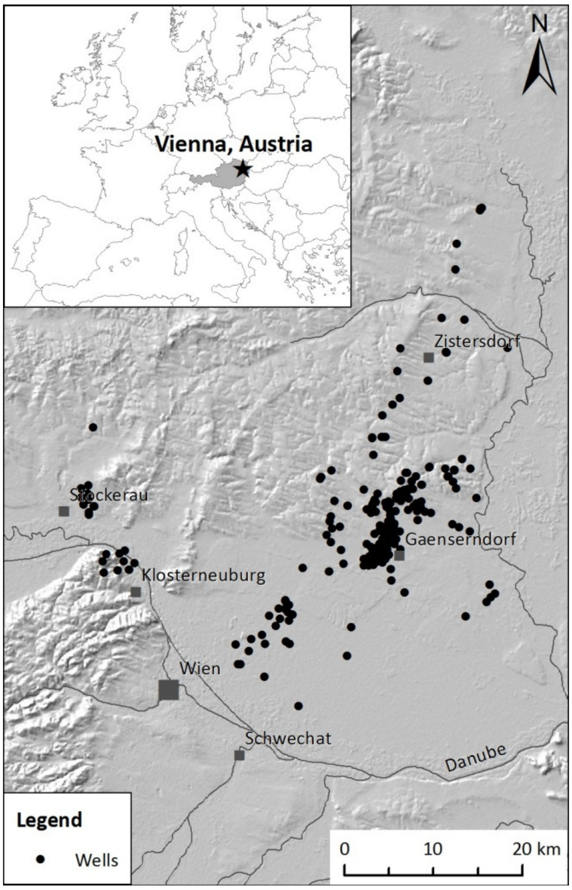

Figure 1: Investigated area and hydrocarbon wells for which performance and economic prospects when operated as DBHE were determined.

The practical execution of this scientific program is facilitated by a temporal and thematic division into two project phases: Phase 1, dealing with the feasibility of geothermal adaptation of existing hydrocarbon infrastructure, is now completed, while phase 2, at present, focuses on hydrothermal development chances in the area of deepest subsidence of the Vienna Basin. One DBHE pilot plant is already operating, while plans for another, hydrothermal facility are being designed. Central to the present contribution is a standardized method of dealing with various existing information, from drilling data to energy demand prognostications, in a way so as to speed up and rationalize the task of screening hundreds or even thousands of wells for their prospective technical and economical suitability to be adapted for geothermal purposes. The methods and outcomes presented below are expected to be relevant to many more regions with a promising share of wells and hydrothermal resources,

2. METHODOLOGY

As for the general layout of the heat supply system envisaged as being constructed around a prospective DBHE, some basic technological assumptions had to be made. Several technological variants were taken into account, all of which, though, can be schematized as shown in **Figure 2**. Accordingly, five components (formation, well or DBHE. heat station, supply lines, consumers) had to be investigated, proper calculation schemata designed and characteristic values for relevant parameters determined, and integrated, together with economic and energy demand considerations, into a technical and economic model of a local district heating system. The subsequent sections deal in turn with those said components.

2.1 Formation Thermal Properties

The study area is, for the most part, located in the Vienna Basin. This is a Neogene pull-apart basin, broken into the transition zone between Eastern Alps and the Carpathian mountain belt, with a SW-NE-extension of about 200 km and a width of approx. 60 km. The Neogene basin fill is mainly composed of sandstones, clay marls and conglomerates. The substructure of these sequences is formed by Calcareous Alpine nappes, and sections of other tectonic units (Flysch Zone, Greywacke Zone and Central Alpine Zone). The lowest level well documented by drilling results is represented by autochthonous Mesozoic strata, mainly of Jurassic age, on crystalline rocks. Large normal faults separate shallow marginal blocks around the flanks of the basis from a system of depressions. The synsedimentary faults created space for deposits up to 3000 to more than 5000 in thick. North of a major NW−SE- trending fault zone crossing the city of Vienna, on the one hand, the deepest depocenters suitable for geothermal development are found, but also, on the other hand, just average thermal conditions with a geothermal gradient approx. 30°C/km. South of the said fault zone some positive thermal anomalies are observed (and utilized by spas).

The hydrocarbon potential of the Vienna Basin is mainly bound to Neogene sandstones, Upper Triassic dolomites and Flysch sandstones (WesseIy, 2006). Approximately 3000 oil wells were drilled, a tenth part of which penetrated the basin substructure. For the present purpose, therefore, lithological and thermal properties of the respective sedimentary rocks had to be established. The available data are owned by OMV, old papers are archived and newer information is stored in the electronic well data base of the company (which to a large extent has already replaced the paper archive).

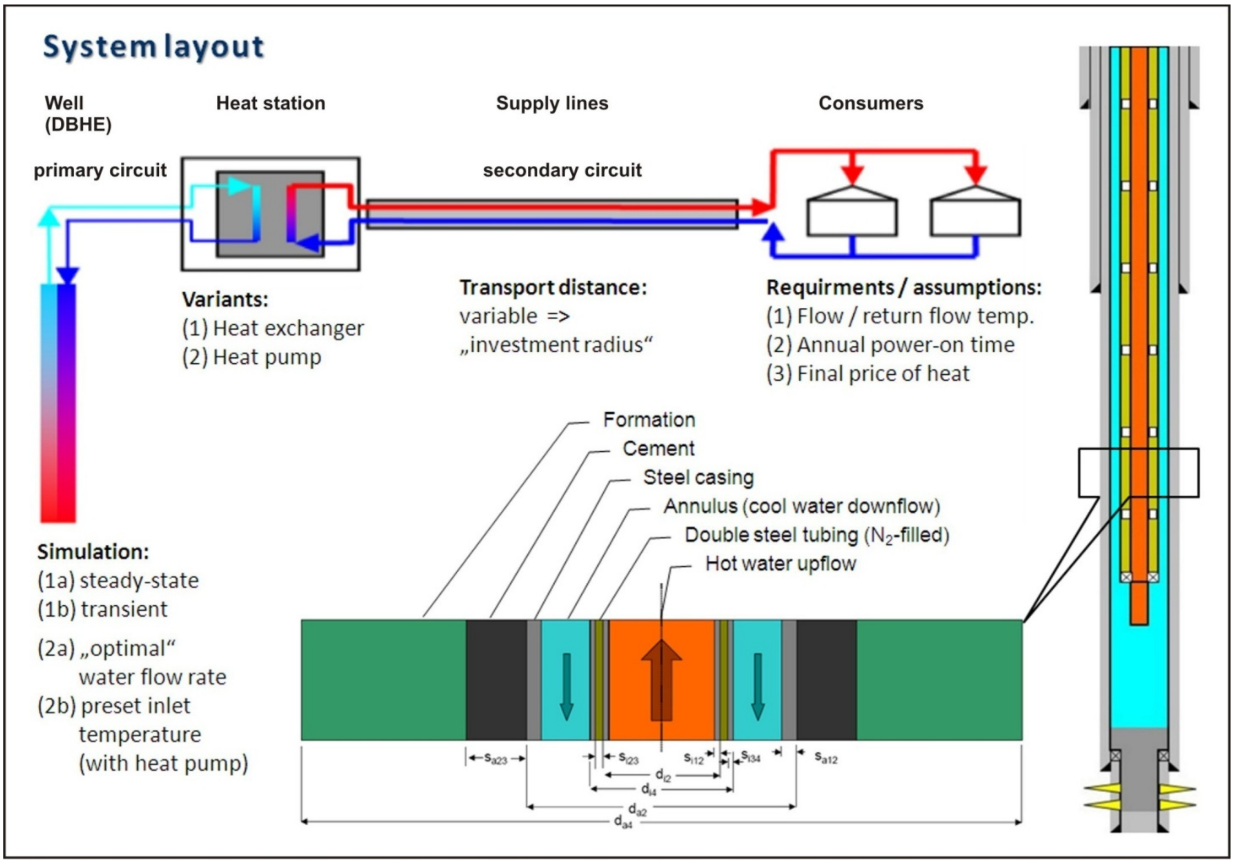

Figure 2: Layout of a local geothermal heat supply system with DBHE. Top – over-all layout; right – coaxial fluid circulation DBHE; bottom – section of DBHE showing radial arrangement of compartments for which geometric and thermal properties have to be established.

Available to the project were technical information concerning the wells as well as analytical findings of hydrocarbon prospection, exploration and production. Of special importance were data concerning the way of liquidation of wells now out of service, as well as results of core analysis, borehole measurements and formation tests. The main technical selection criteria early in the project for applicable wells were a complete casing down to a minimum depth of 2000 m, and a minimum nominal casing diameter of 9 ⅝ in. These criteria were derived from calculations with a steady-state DBHE model to be discussed below. From further technical criteria (mode of casing recovery) approx. 100 wells were selected for close examination, before detailed numerical tools were developed. This is called the "empirical" well selection.

Based on the OMV well data, simplified prediction models for (a) effective thermal conductivity, (b) effective heat capacity and (c) bulk density were designed in order to allow automated calculations of DBHE heat extraction. While parameters (a) and (b), for which applicable lab data were lacking completely, had to be modelled based on mineralogical composition, total porosity and pore fluid conditions as well as ambient temperatures, a simplified approach for parameter (c) based on existing measured data was chosen. Petrophysical lab investigations of drilling cores were still in progress at the time of writing.

2.1.1 Data Processing

More than 500 individual geologic units widely differing in lithologic evolution and tectonic setting had to be covered. For that reason generalized geological layer models focussing on expected distinctions in thermal behaviour and mainly based on core descriptions as well as published sources (Wessely, 2006; Faupl, 2003) had to be defined in a first step. For each generalized layer volumetric fractures of normalized individual rock types have been derived assuming an isotropic distribution of different rock types. Subsequently, average thermal conductivity and specific heat capacity values (for the rock matrix at 25°C) were determined. For conductivity, geometric averaging was applied to allow for anisotropic behaviour (cf. Beck, 1976), whereas for heat capacity, being a volumetric property, simple arithmetic averaging was preferred. Interestingly, published values often do not come with information on the exact measurement conditions, so pure matrix data were sought (Kutasov, 1999; Schöen, 1983) and corrections made for porosity, inferred from data base data, and temperature dependence, also according to the literature (Sass et al., 1992; Kutasov, 1999; currently representative core material is examined in the laboratory at different states of saturation and temperature). Given the overall liydrochcmical conditions a constant pore fluid model (formation brine with approx. 50 g/l Cl) as well as the assumption of complete extraction of hydrocarbons before installation of a DBHE was regarded appropriate.

Porosity and temperature dependence of thermal conductivity and temperature dependence of specific heat capacity, respectively, have been calculated according to the empirical corrections by Sass et al. (1992) and Kutasov (1999) as fellows, Eq. (l) to (3):

$$\lambda_{eff} = \lambda_s^{(1-\phi)} \lambda_f^{\phi} \tag{1}$$

where λ_{eff} and Φ are the effective thermal conductivity and porosity of the bulk rock and the subscripts *s*, *f* refer to solid and fluid, respectively;

$$\lambda_{eff}(T_{Form}) = \frac{\lambda_{eff}(0°C)}{1.007 + T_{Form} \cdot \left(0.0036 - \frac{0.0072}{\lambda_{eff}(0°C)}\right)} \tag{2}$$

Where λ_{eff} and T_{Form} are the effective thermal conductivity and the ambient formation temperature (°C), respectively;

$$c_{p,eff}(T_{Form}) = c_{p,0} + \beta\left(T_{Form} - T_0\right) \tag{3}$$

with $c_{p,eff}$ being the effective heat capacity, T_{Form} the formation temperature, $c_{p,0}$ the heat capacity reference value at T_0 = 25°C and β a proportionality constant.

2.1.2 Sensitivity Study

Regarding transient conditions the accuracy of prediction of DBHE performance is directly proportional to the prediction accuracy of both the formation thermal resistance and formation temperature. In principle these parameters in turn depend on thermal conductivity, heat capacity, bulk density as well as on radiogenic heat production (internal heat sources). In a first step, the influence of internal radiogenic heat sources (U^{238}, Th^{232}, K^{40}) was investigated and found to be insignificant.

The time-dependant thermal resistance can be estimated by the following approach assuming a thermal line source:

$$R_{Form}(t) = \frac{1}{2\lambda_{eff}}\left[\ln\left(\frac{4 \cdot \lambda_{eff} \cdot t}{\rho \cdot c_{p,eff} \cdot (d_B)^2}\right) + 0.806\right] \tag{4}$$

with R_{Form} being the thermal resistance of the surrounding formation (mK/W), λ_{eff} the effective thermal conductivity, ρ the rock mass density (kg/m^3), d_B the borehole diameter (m) and t the time period (s).

Bulk densities based on empirical data and allocated to generalized geological layers as described above show a general standard deviation of 4.3%. Assuming individual maximum prediction errors for modeled values of thermal conductivity and heat capacity in the range of 10% an error analysis of the predicted formation resistance according to Eq. (4) was conducted, with the result depicted in **Figure 3** As can be seen from the figure, the accuracy of predicting thermal resistance of natural rocks predominately depends on the error of estimation of thermal conductivity.

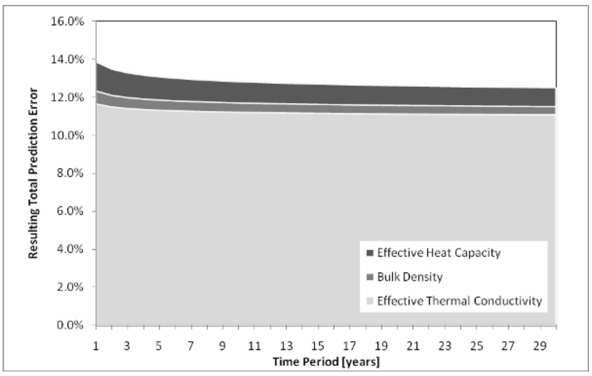

Figure 3: Total error according to transient prediction of formation resistance using assumed individual prediction errors for thermal conductivity and heat capacity of 10% and a calculated individual prediction error for bulk density of 4.3%.

Assuming steady-state, purely conductive heal transfer the prediction of subsurface temperatures based on Fourier's Law is solely governed by thermal conductivity. Therefore, thermal conductivity is the most sensitive rock parameter when determining DBHE heat extraction (> 90% of total resulting prediction error). The effective thermal conductivity, in turn, is mainly dependent on mineralogical composition, pore fracture and ambient temperature of the rock mass. What regards mineralogical composition, detailed error analyses will not be available until finalization of above mentioned petrophysical laboratory investigations. Regarding total porosity, input data seemed quite heterogeneous due to varying overburden depths and facies. The error analysis discovered mean prediction errors of approx. 6% for the effective thermal conductivity and approx. 9% for heat capacity. Error analyses based on literature data published by Kappelmeyer and Haenel (1974) exhibit an average prediction error of ± 5% for temperature corrections according to the above presented approach by Sass et al. (1992) for the temperature interval between 0 and 200°C. The temperature dependence of thermal behavior according to pore fluid properties is negligible. For that reason effective models of thermal conductivity and heat capacity have been calculated for invariant pore fluids at laboratory temperature and pressure conditions.

2.1.3 Standard Layer Models

More than 500 individual geological units were generalized to 159 lithostratigraphic standard layers, covering all major lithologies in all relevant tectonic units, and linked to the original OMV database. These layer-models, in turn, were linked to individual normalized rock types (marl, sandstone, limestone, etc.) by volumetric fractioning. In total, 38 such rock types were assigned the required thermal properties and combined to describe all the 159 standard layers.

Total porosity values were based on empirical data from drill core measurements and geophysical log interpretation. The possible depth dependence of the total porosity due to increasing overburden was considered, but from case studies it was inferred that a static porosity model is entirely sufficient, presumably due to the fact that overburden-related reduction of porosity is already implied in the database of averaged total porosity values.

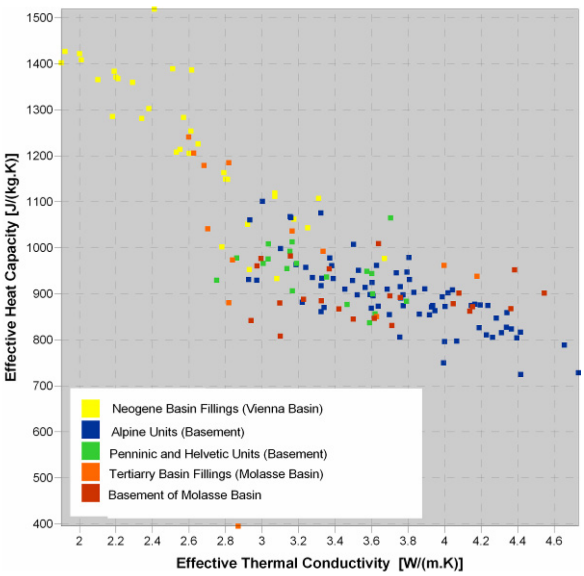

Figure 4: Cross-plot of modeled thermal parameters of standardized lithostratigraphic units, classified according to tectonic environment.

Also, the bulk rock density is of minor sensitivity only, so that available empirical data from drill core measurements have been averaged for each standard layer. Predicted values of effective thermal conductivity and heat capacity of the described model-layers, classified according to tectonic environment, are illustrated by **Figure 4.**

2.1.4 Geothermal Modeling

For the Vienna Basin rather average geothermal conditions were expected, but area-wide maps of the thermal regime were not available at the beginning. Therefore, a simplified algorithm was elaborated based on corrected bottom hole temperatures (BHT) and results of hydraulic drill stem tests (DST). While assuming purely conductive, steady-state terrestrial heat transfer, the prediction of subsurface temperatures was achieved by calculating overall heat flow densities (HFD). Unfortunately, most wells have been drilled and tested in the 1960's and 1970's, when borehole temperatures were of minor interest. So, documentation is rather poor in a great many cases, particularly logging of shutdown and circulation periods before BHTs. As a result, thermal data processing had to focus on painstaking evaluation of relatively few high-quality DST datasets and BHT corrections.

For BHT corrections two different approaches were used. A line-source related graphical correction method based on Lachenbruch and Brewer (1959), supplemented by Homer's method as modified by Fertl and Wichmann (1979) was applied first. Subsequently, a numerical BHT correction (cylindrical source) according to Leblanc et al. (1981) was also used, Eq. (5):

$$T_{Form} = BHT(t) - \Delta T' \left[\exp\left(-\frac{a^2}{4\kappa t} \right) - 1 \right] \qquad (5)$$

where ΔT, κ, a, t are the initial thermal perturbation due to drilling mud circulation (°C), the effective bulk thermal diffusivity of drilling mud and surrounding rock mass (m^2/s), the well radius (m) and the shutdown period (s), respectively.

HFD was calculated following a pure-conduction approach, ignoring internal radiogenic heat sources, by way of inverse optimization of HFD values, which have been assumed as constant over the entire borehole length. The temperature at the i-th boundary of a layered half-space is expressed by the recursion:

$$T_{i=1,n} = T_{i-1} + q \cdot \frac{m_i}{\lambda_{eff,i}} \qquad (6)$$

where q is the heat flow density (W/m^2) and m_i the thickness of the i-th stratum of a layered half-space (m).

The optimization was based on modeled values for effective thermal conductivity. A constant depth increment of only 1.0 m was applied to allow an accurate correction of the dependence of effective heat conductivity on temperature. Iterative optimization of the overall HFD values, then, is achieved by calculating residuals between measured and modeled borehole temperatures. The procedure was applied to 309 wells for which measured borehole temperatures were available.

As a result, an average surface HFD of approx. 68 mW/m^2 was calculated. Toward the Pannonian Basin (to the south-east) significantly elevated HFD values of up to approx. 95 mW/m^2 are observed. The north-eastern margin of the Alps generally exhibits significantly lower geothermal conditions due to crustal thickening and locally confined inflow of meteoric water. Within the Vienna Basin, on the one hand, minimum values down to approx. 45 mW/m2 (presumably related to thick sequences of "cool" sediments still not thermally equilibrated), but on the other hand, to the south of Vienna also local positive heat flow anomalies are observed. They are caused by ascending warm water hydrologically connected to adjacent parts of the Calcareous Alps to the West.

Based on these results, in addition, subsurface temperatures were computed for different depths. The calculated temperature distribution at 2500 m below ground level is illustrated by **Figure 5**.

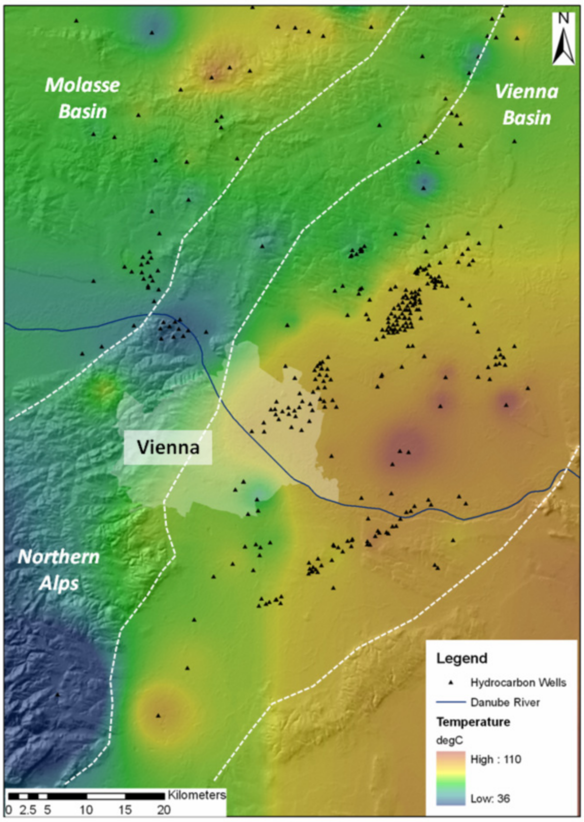

Figure 5: Distribution of calculated formation temperatures at a depth of 2500 meter below surface.

2.2 Borehole Heat Exchanger

In view of the given kind of experience in the hydrocarbon industry what regards drilling and well treatment the coaxial fluid circulation type of DBHE, the operating fluid being water with glycol added, was chosen as the basic technological setting of the study. It contains a coaxial double steel riser tube, with the annulus filled with nitrogen gas at a low pressure (< 1.0 bar). For calculation two numerical models were set up: One for steady-state operating mode, relying on a line source solution for the heat flow from formation to well, and one for transient heat transport numerically solving the heat equation by way of a finite volume model.

From a thermodynamic point of view, the subsoil, as exemplified by a sedimentary basin, mainly consists of horizontal layers of equal physical properties. The DBHE is oriented perpendicular to this structure. Therefore, thermal disturbances produced by the DBHE will expand more or less radially into the earth, and an axially symmetrical treatment of the formation is reasonable. In addition, the DBHE is built in a tube-in-tube manner. In the outer annulus the heat transfer medium (water with some glycol) flows downward and is heated up on its way to the bottom by the heat flux into the well. At the bottom it enters the riser pipe and, while flowing upward again, loses some heat to the down-flow in the outer annulus, since the fluid there has a lower temperature. Obviously, the better the insulation of the riser pipe, the better the temperature of the up-flow is preserved, Compared to the formation, where only heat conduction can be assumed, the energy transport processes within the DBHE are much more due to convection (forced convection of the operating medium, free convection in other fluid-filled spaces). This has to be taken into account in the modeling.

The mathematical model had to be simple enough, on the one hand, so as to understand what's going on when parameters were varied as well as to be solved in adequate time, but sophisticated enough, on the other hand, to represent the relevant physical properties with sufficient precision. The transient behavior of the formation due to energy extraction by the DBHE can be described by Fourier's heat conduction equation in transient form. Due to the axially symmetrical behavior of the formation, it is obvious to use a cylindrical coordinate system, whereby the heat equation becomes

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (7)$$

with radius r, measured horizontally from the centerline, vertical coordinate z, conductibility of temperature α and temperature T as the unknown (result of calculation).

This partial differential equation has been solved by using the finite volume (FV) method, in order to get the temperature of the formation at each point of the discrete grid at each point in time.

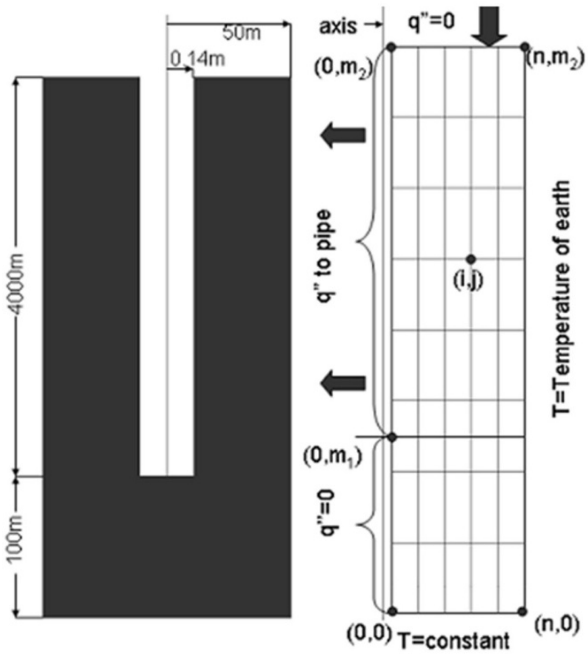

Figure 6: Transient DBHE model discretization of the surrounding formation.

Figure 6 shows the discretization of the formation and the necessary boundary conditions. Since the earth below the DBHE has some influence too, a certain volume there is represented as well. At the inner side of the hollow cylinder the formation is in interaction with the DBHE. To allow for this interaction, the heat flux has been defined as boundary condition. The solution of the heat conduction equation gives the temperature at this boundary, which is then used to calculate the heat transfer from the boundary of the formation into the well and returns the heat flux as a result. The DBHE has been divided into sections of the same height as those of the formation (**Figure 2**). Also, the discretization in time of formation and DBHE has been done with equal time steps. The DBHE has been modeled quasi-stationary, since the convective energy transport in the well is much faster than the energy transport in the formation due to conduction.

The steady-state model, based on 3 simplified line-source solution according to Kutasov (1999) for heat exchange between formation and well, and standard engineering solutions (VDI (2006) was used as a reference work) for iteratively calculating temperature and pressure within the well, and used for pre-calculations and determination of first selection criteria of minimum well depth and casing diameters. Thereby, it was decided that of all the geographically relevant wells contained in the OMV well data base only those with a depth > 2000 m and inner casing diameters down to this depth of at least 9 ⅝ in should be selected for further study. Of these, in turn, many mostly dated wells had to be excluded because of incomplete data. Finally, 270 wells (see **Figure 1**) were sufficiently well documented to merit close examination. For this purpose, a computer program called Geothermal Planning Toll (GPT) was designed, suitable for batch-calculation of many wells. Both above mentioned modeling methods are implemented in this program and can be combined to a certain extent, saving calculating time.

2.3 Heat Station

At the heat station the thermal energy from the primary circuit including the DBHE is either transferred simply by means of a heat exchanger to a secondary circuit (supply system) or, in addition, raised to a higher temperature by means of a heat pump. The heat exchanger version is viewed under the condition that the energy being delivered by the DBHE at some optimum operating state can, for a certain time of the year, be entirely used up by the consumers. The water mass flow rate, then, is adjusted so that a maximum thermal energy yield is achieved in relation to the power required for driving the fluid flow. As an index for optimum conditions the cost relation between obtained heat and spent power is used.

A heat pump is used to attain or uphold a pre-defined supply temperature in the heating system. To achieve this, there must be accepted a certain deviation from optimum operating conditions as defined above, toward a lower mass flow rate, in order to reduce the necessary temperature rise (well top temperature as a function of mass flow rate exhibits a maximum at small flow rates and to the left of the optimum point). As the energy raising temperature in the secondary circuit is for the most part taken from the primary circuit, the return temperature of the latter can be lowered, so that the usual heat loss into the formation at low depths (for present purposes down to approx. 1000 m) can be avoided. This, as well as the elevated temperature gradient toward the well, enhances the DBHE performance.

In addition, a third operating mode, applying absorption refrigeration for cooling, was considered. In the end, though, for technical and economic reasons, this variant had to be dropped altogether, the criterion being too low a temperature level attainable by DBHE under prevailing natural and economic conditions.

2.4 Supply Lines

In the model system used for analysis, a single supply line including flow and return flow connects the heat station with a release unit where the heat is transferred to the users. The length of this model supply line determines the maximum distance, for which − cost effectiveness taken for granted − investment in a local district heating system may be considered ("investment/economic radius"). Also, it can he viewed as maximum cumulative length of a supply network. Because this is a parameter that, for calculation purposes, can be changed at will, it is possible to illustrate the calculated profitability for each well operated as a DBHE and for each given economic index method by drawing an "economic radius" around the well. That means, in order to meet the minimum requirements for a certain payback period, annuity or internal rate of return, an appropriate user has to be inside an economic radius.

2.5 Consumers

While with regard to the wells themselves, required data as are location, depth, piping, geology, thermal underground parameters etc. are comparatively well known, and it was possible to develop numerical models for calculating DBHE performance almost accurate, as shown above, for the consumers, usually no accurate data are available and many assumptions have to be made. The reason is that the energy demand of a user heavily depends on the type of user. For example, a one-family-house requires heat energy for about 1800 to 2000 full load hours during winter season, whereas further differentiations have to be considered due to heating system (e.g. low temperature heating system like floor healing or high temperature heating system like radiators) which influences the required temperature level. On the other hand, an industrial plant often requires heating energy all over the year, whereas the temperature level can differ over a wide range. Other variations are possible due to a fluctuating heat (power) demand during each year

For each calculation three parameters, which as such are variable but commonly not known empirically except in connection with a concrete project, have to be given specific values (as a function of time or not). These are (a) flow and return flow temperature, (b) annual operating time or number of full load hours, and (c) the attainable final price for the heat used up by the consumers. Pre-calculations already showed that regarding system temperature (a) in any case one has to consider "low energy" conditions (chosen characteristic values: flow temperature 40^{o}C and 60°C with heat exchanger and heat pump, respectively, return temperature 35^{o}C). Also, it became clear that (b) supplying heat for the usual heating season only (approx. 2000 full load hours per year) will be not sufficient to achieve positive economic output, to say the least. With the assumption of a characteristic value of 5000 full load hours per year it is also clear that users with a high and rather constant annual heat demand, that is, in the public, industrial and agricultural sectors, will have to be envisaged as potent consumers in any case. Finally (c), the selling price of the delivered heat energy has a big impact on economic efficiency. In order to be competitive with other energy forms (conventional district heating, gas, electricity, fossil fuel etc.) the geothermal energy price is limited by the price applied by the other energy systems available at a particular location. Therefore, the final price for consumed heat at least will have 10 be lower than the price of the most competitive alternative energy form (gas).

So, because of the described complexity and the multitude of possibilities it is impossible to set detailed specifications of users which are appropriate for all locations in the vicinity of potential DBHE. Therefore, the following assumption was made for determination of economic efficiency: There is an ideal user who requires all available energy; the system temperatures given above can be constantly upheld, and the annual operating time (full load hours) as well as the heat demand within a year can be chosen (for example, set to above mentioned values).

3. GEOTHERMAL PLANNING TOOL

All final calculations were performed by the Geothermal Planning Tool (GPT) already mentioned. This software tool was created for fast evaluation of a high number of wells and a range of economic conditions and can be used with local or remote (encrypted data transfer) databases. Thermodynamic properties and well geometries (defined by depth, casing and tubing specifications and material parameters) are automatically extracted from the database. Tubing for the riser can be added automatically. An integrated well log viewer enables the user to review even complex situations and to identify data errors like missing entries or unlikely values quite easily (cf. **Figure 7**).

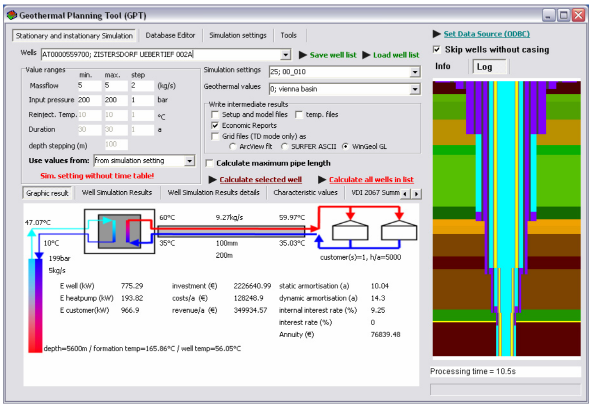

Figure 7: Geothermal Planning Tool with log viewer.

Based on stored criteria like minimum depth or casing conditions wells not meeting the requirements are excluded from further simulation. Varying several parameters like mass flow, input pressure or reinjection temperature the most economic operating conditions are determined. The implemented financial analysis estimates all costs already mentioned like retrofitting, liquidation, costs for heat exchanger, heat pump and pipe network (all parameters are stored in the database and can be adjusted to local situations).

Thereby it is possible to calculate the maximum length of the heat distribution network, dynamic amortization period or internal interest rate of the project in order to represent overall cost efficiency.

Computing the thermal development of the well and surrounding area allows estimating the impact on environment and if, for example, stable conditions (within the operating duration of the well) are reached or not (**Figure 8**). Also, all the major software modules can be accessed individually for sensitivity analysis of single parameters.

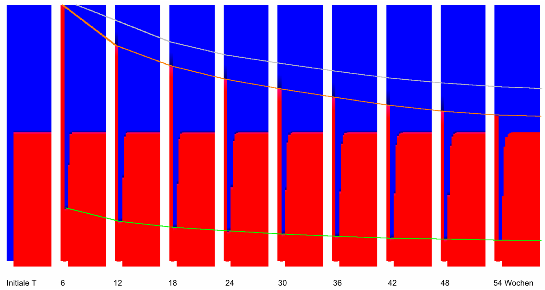

Figure 8: Temperature field of a well (outer left side of each block) and nearby formation (radius 50 m) during first year of operation. Isotherms: Gray – 46°C (up-flow); orange – 45°C (up-flow); green – 45°C (down-flow). Red areas: > 45°C.

4. RESULTS

The specific results of the study (detailed for specific wells, for example) were not meant to be published, but the outcome can be reasonably generalized. One conspicuous upshot of the study was the fact that many wells which at first seemed to offer significant geothermal prospects, even with the present method of DBHE, and therefore were included in the "empirical" well selection early in the project, had to be excluded again after detailed economic considerations. There are several reasons for this: (a) Wells that were selected because of great final depth often include open-hole suctions, which have to be lined in the course of DBHE construction. The costs obviously endanger the economic efficiency of DBHE which require such retrofitting. Otherwise, if the usable depth is set to the section with casing intact, the economic result is often the same because of reduced performance. (b) Formerly liquidated wells, which were reopened and modified as DBHE, have to be liquidated again at the end of their life-time. For this purpose, the owner is legally obligated to put down a reserve. Taking this into account in some cases already leads to a negative economic assessment. As with the well treatment costs generally, liquidation costs tend to exert an increasingly negative economic influence with increasing well depth. (c) In some cases, wells were selected not because of an appropriate depth range, but because of a positive temperature anomaly in the surrounding formation. Unfortunately, even a documented positive influence of the anomalous thermal conditions could never outweigh the other factors reducing performance.

Differences between operation modes can be summarized as follows: (a) Calculations have shown that cooling by way of absorption refrigeration is not economic due to temperature levels too low for the purpose. (b) However, with heat exchanger or heat pump technology dynamic payback periods of less than 15 years and internal rates of return higher than 10% can be achieved under favourable conditions ("high capacity" user near the well, among others). (c) Under thermal conditions of the investigated area the heat pump always does better than the heat exchanger.

Regarding energy economics the following factors must be taken into consideration: (a) Final heat prices charged by local district heating suppliers are mostly on the order of 70 EUR/MWh. A large part of this money has to be spent on the construction and operation of the supply network. Therefore, the cost price of energy rarely is above approx. 25 and more often than not is even below 20 EUR/MWh.

But actually, to attain positive economic output for a DBHE in the investigated area, the heat price has to be set higher than the mentioned cost price accepted by established heat suppliers. The upshot of this is that the obtained thermal energy is not suited for feeding it into an existing district heating system, but for supplying users directly instead.

Even the most interesting (and deepest) well in the Vienna Basin can be economically operated with a selling price of used heat no less than 50 or 55 EUR/MWh, depending on operating mode (the calculated minimum price in order for a heat pump to be economical is approx. 30 EUR/MWh). (b) Therefore, the results of the study are valid only with the prerequisite that the DBHE operator can afford and is responsible also for getting the extracted heat to the users (construction and operation of the district heating system; under such conditions the applicable final heat price was set to approx. 72 EUR/MWh). Furthermore, it is not expected that price policy options allow incentives to be offered for users of competing energy forms to change over to geothermal energy, supplied by DBHE (with hydrothermal energy this maybe different).

Under all of the conditions defined above, for the entire Vienna Basin, 21 hydrocarbon wells can be documented to offer economically viable prospects for utilization as DBHE. Of all the liquidated wells, only 3 merit closer inspection. And only one of these, in addition, is within technical and economic reach of settlement areas, with plots as yet not used for building. Obviously, retrofitting costs are in all but a very few cases too high for attaining cost effectiveness. Of the 21 selected wells. 18 wells are still in service. Fortunately, most of these belong to a single oil field and are close to attractive designated settlement areas. Therefore, a significant potential for utilizing hydrocarbon wells of the Vienna Basin as DBHE (coaxial fluid circulation method) lies in the future. In view of the common liquidation practice these wells should be marked for conservation and, in addition, the mining authority as well as the municipalities should be given notice of the opportunity to adapt the wells for geothermal purposes. In these cases it is conceivable that the awareness of said opportunities may even influence land development schemes. This would require, though, that planned developments were actively observed (in cooperation with regional planners) and opportunities or intentions actively communicated to local decision makers and planners.

Because of the intricacies of defining the consumer side of the chosen heat supply model system as well as the impossibility of knowing in advance the operating conditions of future DBHE, the entire energy production potential of the DBHE in the Vienna Basin cannot be thoroughly established. As a rough but founded estimate one can say that the potential of DBHE with heat exchanger or heat pump add up to approx. 6.5 MW and 13 MW, respectively. Assuming, on the user side, a standard annual full load time of 5000 h/a and the capacity to use up all delivered heat, the calculated annual energy amount delivered would become approx. 32500 and 65000 MW/h, respectively. In any case, an annual operating time much longer than the usual heating season must he achieved in order to get economically viable results. An additional condition for the presented calculations to represent (future) reality to an acceptable degree will be to achieve a rather high and constant level of consumer heat use and thereby a sufficiently low return temperature over the annual operating time. For all these reasons, it is virtually imperative to cooperate with users in the public and/or industrial and/or agricultural sectors, each with a sufficiently high demand of warm water and process heat.

5. CONCLUSION

270 wells drilled in the Vienna Basin (and some minor areas in nearby) by the Austrian oil company OMV were investigated for their potential to supply geothermal heat in an economic way and on the basis of deep borehole heat exchanger (DBHE, coaxial fluid circulation) technology, in connection with either a heat exchanger or a heat pump for energy transfer to the supply lines (secondary circuit). The results show that under regional thermal and economic conditions it is difficult to achieve a return of investment even on a long-term basis (30 yrs) for all but a very few liquidated wells and for most wells currently still in service, too. Of 270 wells investigated, no more than 3 liquidated and 18 operating wells were assigned economically viable chances of being modified as DBHE.

The obtained heat is, for economic reasons, not suited for feeding into an existing district heating system for a cost price common in the business. Instead, the DBHE operator should charge like one of the established supply companies, and in exchange will have to operate the network himself. Also, a high number of annual full load hours (on the order of 5000 h/a) has to be attained, which will be possible only when successfully involving users in the public/industrial/ agricultural sectors in any real project.

Irrespective of the specific results for the investigated area (Vienna Basin) the numerical research tool (GPT - Geothermal Planning Tool) developed in the course of the project and integrating the complete set of necessitated technical and economic parameters and calculations, offers the additional advantage of (a) geothermal energy planning with a backing by well founded numerical estimations, (b) quick potential estimates in various areas (given a suitable data base) and (c) quick adaption to changing economic conditions (price development etc.). For future work, the GPT shall be applied to other regions where conditions are more favorable.

With this in mind, one can ask, for instance, the following question: What geothermal boundary conditions would have to prevail in the Vienna Basin (or any other sedimentary basin of comparable buildup) so that a DBHE can be run for feeding the heat into a district heating system operated by an established energy supply company (which will accept a cost price for heat of no more than approx. 20 Euro/MWh) under otherwise similar economic circumstances? For a DBHE on the model of the single best suited well in the Vienna Basin the answer is: The geothermal gradient would have to be on the order of 70−80°C/km (approx. 2½-fold the value of the one actually prevailing in the Vienna Basin), corresponding to a terrestrial heat flow density of approx. 160 mW/m^2. In Europe, in fact, there are very few regions which can offer such favorable conditions.

Finally, and again for thermal and economic conditions prevailing in the Vienna Basin and Austria or, for that matter, sedimentary basins and industrialized countries in general, some rules of thumb regarding interesting wells to be modified for operation as DBHE can be formulated: (a) Wells that are conserved or still in operation should have more than approx. 3000 m of usable depth; (b) liquidated wells should have approx. 4500 m of usable depth; (c) usable means continuously cased and not perforated. (To run additional casing into open hole sections is generally not economical.)

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